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Volume 17 OCTOBER, 1928 Number 4

SPECTRA OF MERCURY AT ATMOSPHERIC PRESSURE

By W. H. Crew and L. H. Dawson

ABSTRACT

Light from a mercury arc in quartz, operating at atmospheric pressure, and excited by various electrical means was photographed through a quartz spectrograph.

Line Spectra: With very high currents through the arc some thirteen lines were found to be self-reversed, two of which are spark lines. The reversal of one of these (λ1942) supports the view of Carrol, Turner and Compton that it is a member of the first doublet of the principal series of Hg^+. Lines of the diffuse series of Hg appear to be the most readily reversed.

Continuous Spectra: With relatively low currents through the arc the continuous spectrum appears in four discrete bands, three of which have intensity maxima lying close to the three spectral series limits: λ4580; λ3320; λ2240. A modification of Bohr's theory, which attributes bands of continuous radiation to the recombination of electrons with atomic or molecular ions, is found to agree very well with the observed facts. From theoretical considerations it is shown that a velocity distribution of the free electrons in the arc, corresponding to a temperature 2500°K, gives an intensity distribution of continuous spectrum in agreement with that observed. Certain observations by Rayleigh are found to be compatible with this theory.

Spectrograms of a mercury arc operating at atmospheric pressure and excited by various electrical means have been made. In the line spectrum there have been observed some new self-reversals which belong almost exclusively to the diffuse series, and indeed seem to favor the more diffuse lines of that series; furthermore, there have been found very strong bands of continuous radiation which are associated with the continuous spectrum due to recombination of electrons with positive ions. The recombination theory of the continuous spectrum was originally established by Bohr, modified by Wright[1] and others[2] to fit the observed spectrum of hydrogen, and recently has been applied by Mohler[3] to account for the continuous spectra

[1] Wright, Nature, *109*, p. 810; 1922.

[2] Nicholson, Monthly Notices, *85*, p. 253; 1925. Crew and Hulburt, Phys. Rev., *28*, p. 936; 1926.

[3] Mohler, Phys. Rev., *31*, p. 187; 1928.

of caesium and potassium. The bands of continuous radiation in mercury observed by us are identically those seen in fluorescent mercury[4] and in low voltage arcs.[5] In the discussion of these bands it is not necessary to specify whether they originate in an atom or a molecule, it is sufficient to attribute them to recombination taking place in a strong electric field, that of a neighboring atom or ion, or possibly of an atom bound in molecular union.

APPARATUS

The arc consisted of a U-tube of clear, fused quartz, open at both ends, and filled with mercury; the lower part of the tube was bent forward and upward, as may be seen in Fig. 1, and constrictions were made in the middle portion and at the upward bend of each

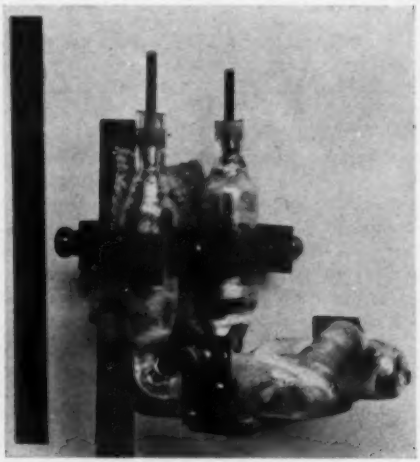

FIG. 1. *Quartz mercury arc.*

leg, and iron wire electrodes were dipped into the mercury at the open ends of the tube. To start the arc the mercury was vaporized in the middle, constricted portion by means of a flame or an electrically heated resistance wire, the discharge taking place between the ends of the broken mercury column.

Various electrical methods were used to excite the arc; the line absorption spectra were produced most readily by direct current from the 110-volt mains or by a condensed discharge from a 1 KW, 30 KV,

[4] Houtermans, ZS. f. Phys., *41*, p. 140; 1927. Asterblum, ZS. f. Phys., *43*, p. 427; 1927.
[5] Rayleigh, Proc. Roy. Soc., *A114*, p. 620; 1927.

25 cycle transformer in parallel with a 0.012 micro-farad condenser. The bands of continuous spectra appeared under high tension excitation, either from the secondary of a transformer, from the output circuit of a high frequency radio transmitter, or from a 2500 volt dc motor-generator set.

Under conditions of low potential and high current, the luminous discharge appearred to fill practically the entire inside diameter (3 mm) of the tube, though there was undoubtedly a thin layer of unexcited vapor next to the wall. The high tension discharges produced fine luminous threads which danced about along the axis of the tube, their width increasing with the current through the tube.

LINE SPECTRA

Spectra of the arc under direct current excitation, (Fig. 2a) showed broadened arc and spark lines on a background of more or less uniformly distributed continuous radiation. Increasing the current through the arc from 2 to 25 amperes caused the lines to broaden and, in the case of some lines of the diffuse series, to become self-reversed. Under the influence of a condensed discharge (Fig. 2b) the lines again

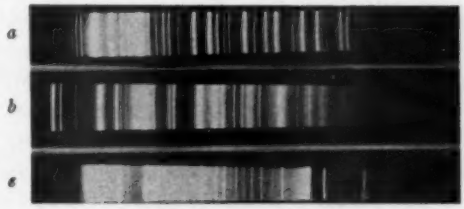

FIG. 2. *Mercury spectra, excited by (a) direct current; (b) condensed discharge; (c) high voltage, alternating current.*

appeared very broad, the spark spectrum was greatly enhanced, especially in the ultraviolet region, and thirteen lines were observed to be self-reversed.

Table 1 gives the wave lengths and notation of these reversed lines, of which two are spark lines, eight are arc lines of the diffuse series, and three are inter-combination lines of the arc spectrum. From this it appears that lines of the diffuse series are the most readily reversed: this is in agreement with Hori[6] who observed the spectrum of mercury excited by Anderson's exploding wire method and reported

[6] Hori-Memoirs of Coll. of Sci, Kyoto Imp. Univ, A9, p. 379; 1926. Also Inst. of Phys. and Chem. Res. Sci. Papers, 4, p. 59; 1926.

that "the lines of the diffuse series could be reversed at an earlier stage than those of the sharp series." The question was raised by Hori, however, whether or not this might be due to the photographic plate

TABLE 1. *Lines observed to be self-reversed.*

Diffuse triplets	Combination
3650 $(2^3P_2-3^3D_3)$	3131.8$(2^3P_1-3^1D_1)$
3131.5$(2^3P_1-3^3D_1)$	2655 $(2^3P_1-4^1D_1)$
3125 $(2^3P_1-3^3D_2)$	2536 $(1^1S_0-2^3P_1)$
2967 $(2^3P_0-3^3D_1)$	
3021 $(2^3P_2-4^3D_3)$	Spark lines
2653 $(2^3P_1-4^3D_1)$	1972
2652 $(2^3P_1-4^3D_2)$	1942
2534 $(2^3P_0-4^3D_1)$	

lending itself more readily to the reversal of lines of a diffuse character. To test this point we have taken spectra with various times of photographic exposure, and have not observed any sharp line to be reversed.

In Fig. 3 is an energy diagram showing the electron transitions corresponding to some of the arc lines of mercury; the dashed lines representing the transitions found by us to be reversed. All of these

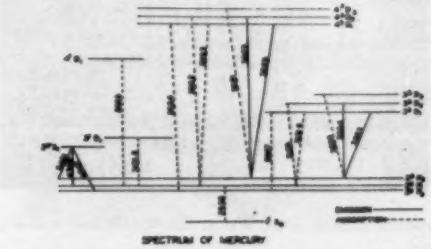

FIG. 3. *Diagram of lower energy levels of the mercury atom.*

eleven reversed lines, excepting the resonance line λ2536, represent electron transitions starting on one or another of the 2^3P-levels; six start from 2^3P_1, two from 2^3P_0, two from 2^3P_2, all end on the various D-levels, one each on 3^1D_1, 4^1D_1, 3^3D_2, 4^3D_2, 3^3D_3, 4^3D_3, and two each on 3^3D_1 and 4^3D_1. We see here a one-to-one correspondence between the transitions which terminate on the $3D$- and $4D$-levels.

The energy levels 2^3P_0 and 2^3P_2 are often called "metastable levels" because spectral lines corresponding to transitions from these levels to the normal 1^1S_0-level are not observed, except under unusual condi-

tions[7] and it is believed that electrons ordinarily escape from these levels only when the excited atom makes a collision with another body. Consequently, at low pressures, collisions are infrequent and there will be an accumulation of electrons on the metastable levels. On the other hand, at the pressure and temperature of the mercury in the present experiment, the time interval between collisions is calculated to be about 10^{-9} seconds,—an interval shorter than the excited life[8] (10^{-7} seconds) of an atom in the 2^3P_1-state. Under these conditions there will be no accumulation of electrons on the metastable levels in excess of those on the 2^3P_1-level, and furthermore, since the latter level is supplied with electrons from the intense absorption of λ2536, and the other two levels receive no electrons by absorption, the 2^3P_1-level should be the most abundantly populated. Because of the greater number of electrons on the 2^3P_1 level, it is therefore reasonable to find more electron transitions in absorption starting on this level.

In each of the triplets 2^3P_2–$3^3D_{\substack{3\\2\\1}}$ and 2^3P_2–$4^3D_{\substack{3\\2\\1}}$ only the short wave length member appears reversed. We note with interest, however, that the three lines of each triplet are approximately of equal intensity, but that the self-reversed member is the most diffuse one in each case. This fact substantiates the observation previously stated that lines of a diffuse character appear to undergo reversal more readily than sharp lines.

Two spark lines were observed to be self-reversed; both were broad in emission, but the reversal of λ1942 was two or three times as broad as that of λ1972. According to Carrol's[9] classification of the spark spectrum of mercury, the line λ1942 is the long wave-length member of the first doublet of the principal series of Hg^+ (the other member being λ1650). This view received experimental verification by Turner and Compton[10] who found that λ1942 was partially absorbed in passing through a gas of mercury ions; and also by Déjardin[11] who obtained this line reversed in a spark between Hg-Cu electrodes. Our observation, along with these other, establishes rather definitely the correctness of Carrol's classification. The "Rydberg doublet" (λ2225 and

[7] Wood, Phil. Mag., *4*, p. 466; 1927. Rayleigh, Proc. Roy. Soc., A*114*, p. 620; 1927. Takamine, ZS. f. Phys., *37*, p. 72; 1926.

[8] Wien, Ann. der Phys., *73*, p. 483; 1924.

[9] Carrol, Roy. Soc. Phil. Trans., *225*, p. 357; 1926.

[10] Turner and Compton, Phys. Rev., *25*, p. 613; 1925.

[11] Déjardin; Ann. de Physique, *8*, p. 424; 1927.

λ2848), at one time believed to be the resonance linesof Hg^+, showed no indication of reversal.

The classification of λ1972 is not definitely known,[12] but the fact that we find it reversed suggests that it corresponds to the second step of a dual absorption in a Hg^+ ion or is a resonance line in a Hg^{++} ion. The self-reversal of λ1942 indicates a relatively high concentration of Hg^+ ions in the arc; but it seems rather doubtful that the concentration of Hg^{++} would be sufficiently great to reverse the resonance line of that ion.

CONTINUOUS SPECTRUM

The continuous spectrum was not only enhanced by a high tension low current discharge, but also appeared in discrete bands which were identical with those observed by Houtermans[4] and others in fluorescing mercury vapor, and by Rayleigh[5] in a discharge from a Wehnalt cathode.

Fig. 2-c is a spectrum excited by current from the secondary of a 1 KW, 30 KV, 25-cycle transformer; practically identical spectrograms were obtained by excitation from a 60-cycle and a 500-cycle transformer, and also from the antenna circuit of a crystal-controlled radio transmitter operating at 4000, 8000, and 16,000 kilocycles. The line spectrum is sharp throughout. A weak band of continuous radiation begins at λ5000, rises to a maximum at about λ4500, falls off gradually to λ4000. A more intense band extends from λ3600 to λ3100 with a maximum at λ3300. A third band commences rather faintly at about λ2600 and increases in intensity toward the shorter wave lengths to an abrupt cut-off at λ2535, and a fourth one commences at λ2400, rises rapidly to a maximum of intensity at λ2350, and extends with gradually diminishing intensity to the limit of the spectrograph. (A densitometer graph showing these bands is given in the top curve of Fig. 6.)

In Fig. 4 are spectra showing the transition between the discharges at low voltage high current (500 ma) and high voltage low current (30 ma) excited by a 2500 volt dc generator with a variable series resistance. With the larger currents through the arc one sees not only a broadening of the lines, but also what appears to be a broadening of the bands which fill in the gap to the short wave-length side of λ2536.

[12] Déjardin, (loc. cit.) records two lines, λ1972·72 and λ1972·10: the former he attributes to the ion Hg^{++}, the latter has not been identified.

In using the condensed discharge it was found that if one electrode was disconnected the arc shone with a feeble, but distinctly greener glow.

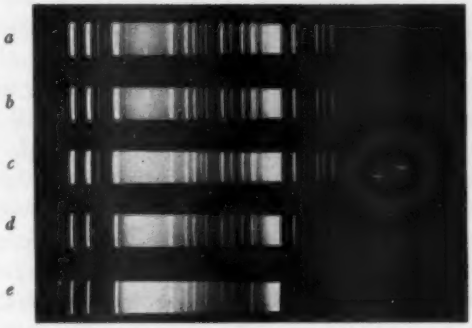

FIG. 4. *Mercury spectra excited by direct current at (a) 85 v, 500 ma; (b) 90 v, 350 ma; (c) 100 v, 250 ma; (d) 125 v, 120 ma; (e) 300 v, 30 ma.*

From its spectrum, Fig. 5, it is seen that the line spectrum is suppressed, the bands being relatively very intense, and in general the radiant energy is shifted toward the red end of the spectrum.

FIG. 5. *Highly damped condensed discharge in mercury.*

A determination of the wave-length limits of the several spectral series of mercury (Fowler "Report on Series in Line Spectra" pp. 148, 149) revealed a rather marked correspondence between these limits and the positions of the intensity maxima of the continuous bands. This may readily be seen by reference to Table 2, in which the first column gives series names and notation of the lower energy levels of

TABLE 2. *Spectral series of Mercury, their wave-length limits, and positions of observed band maxima.*

Series, and notation of final level		Limit in A	Position of band maxima in A
Triplet, Principal,	2^3S_1	4590	4500
Singlet, Sharp and diffuse	2^1P_1	3320	3300
Triplet, Sharp and diffuse	2^3P_2	2490	2350
	2^3P_1	2240	
	2^3P_0	2150	
Singlet, Principal	1^1S_0	1190	—

each series; in the second column are the wave-length limits of the series, and in the third column the positions of the band maxima. The band observed at λ2600 has been omitted in this table since, from its position and its character, which is not at all like the others, it does not appear to belong to this group.

The recombination theory of the continuous spectrum described by Wright[1] and others,[2,3] is in good agreement with the relation between bands and series limits as indicated in Table 2. This theory associates a band of continuous radiation with each spectral series due to free electrons plunging into the lower energy levels of positive ions; the distribution of intensity depending upon the mean kinetic energy of the free electrons (i.e. the temperature of the electron gas) and the deficiency of outer orbits among the ions with which the electrons recombine.

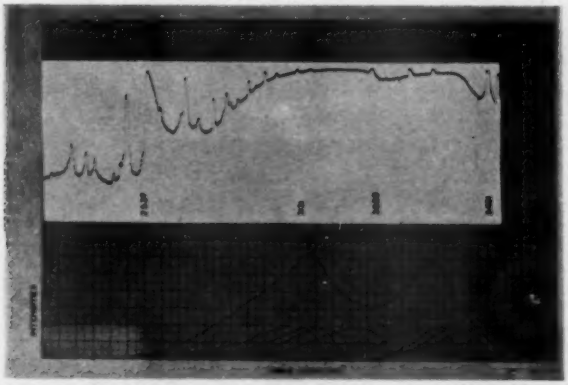

FIG. 6. *Observed and calculated curves of intensity variation in continuous spectra of mercury.*

In the lower part of Fig. 6 are plotted a few intensity curves for two of the series, the values being calculated from an equation derived in another paper,[13] choosing a value of $T = 2500°K$ for the temperature of the electron gas. The top curve of Fig. 6 is a densitometer graph of a plate bearing a spectrum of the continuous radiation bands; the middle curve is a summation of the intensity curves plotted below, but omitting the dashed ones since they represent the improbable cases of atoms having very high deficiencies of orbits. It will be seen that there is rather close agreement between the limits and the posi-

[13] Crew and Hulburt, Phys. Rev., *28*, p. 938; 1926.

tions of the maxima of the observed and calculated intensity distribution curves. (The absolute values of intensity are, of course, distorted on the densitometer graph due to the non-linear blackening of the photographic plate and the varying dispersion of the spectrograph.)

The identification of the λ2350 band with the 2^3P series limits is not altogether satisfactory, for the rapidly changing dispersion in that region makes the position rather doubtful. It was thought that the gap in the continuous spectrum in this region (λ2350—λ2536) might be due to self-absorption in the arc; accordingly experiments were made in which light from an external source was observed after passing through the excited vapor of the arc. No absorption was observed, however, so that it appears that no continuous radiation of that wave length is emitted by the atoms under the conditions which produce the gap.

DISCUSSION

Rayleigh[14] concludes, from his experiments with luminous vapor from a mercury arc, that the "band spectrum derives its energy from the store which maintains the line spectrum." This statement we regard as being in keeping with the idea set forth in the foregoing theory; namely, that the source of both line and band spectra is essentially the atom, and even though the radiating atom is joined to another in molecular union, its emissions are modified, but not shared by its companion.

Rayleigh's observations of luminous mercury vapor, as it is pumped away from the arc, show that the continuous spectrum persists for at least 2×10^{-4} seconds, whereas the line spectrum dies out in much less time. Since the life of a positive ion is about 10^{-4} seconds, he concludes that this persistent radiation preceeds from atoms completely ionized; a fact which is essential in the recombination theory of the continuous spectrum. But Phillips[15] has found these bands (at least those lying on the long wave-length side of λ2536) in vapor excited by λ2536 alone. If the theory is to hold for this case, one is forced to assume that ions are formed by a cumulative absorption of energy, an assumption recently justified by Rouse and Giddings.[16]

The preponderance of continuous radiation in the spectrum of Fig. 5 indicates a relatively large proportion of positive ions in the arc. We account for this by the fact that the 25 cycle condensed

[14] Rayleigh, Proc. Roy, Soc., A*108*, p. 271; 1925.
[15] Phillips, Proc. Roy. Soc., A*89*, p. 118; 1913.
[16] Rouse and Giddings, Proc. Nat'l. Acad. Sci. *11*, p. 514; 1925.

discharge was very highly damped, so that for only an instant at the beginning of each half cycle, excitation and ionization take place; within the next 10^{-7} seconds[17] all excited atoms will return to their normal state emitting the line spectrum, and during a period a thousand times as long (about 10^{-4} seconds) the positive ions will recombine with electrons and emit the continuous spectrum. In the case of less highly damped discharges, the excitation of atoms would take place many times during each half cycle giving greater prominence to the line spectrum.

Rayleigh[5] describes an experiment in which he quenches the blue-green band of continuous radiation by locally heating the tube containing luminous mercury vapor; and in Spectrum VI, Plate 44, of his paper he shows two spectra which are identical except that in the one the 2^3S_1 band (at λ4500) is quenched. According to the recombination theory the disappearance of this band would indicate that no electrons are plunging into the 2^3S_1 level and consequently there can be no emission of the $2^3P_{\substack{2\\1\\0}}-2^3S_1$ triplet (λλ5461; 4358; 4047); and, to be sure, two of these lines are distinctly seen to disappear with the band. (The green line does not appear at all on the spectrogram.)

This rather general theory of the continuous spectrum is by no means final; there are phenomena yet to be explained, as for example, the flutings reported by Rayleigh,[5] Mohler and Moore,[18] Volkringer,[19] and seen on some of our own plates; but the present agreement of theory with the continuous spectra of hydrogen, caesium, potassium, and mercury would indicate that details may be taken care of by further modification.

NAVAL RESEARCH LABORATORY,
BELLEVUE, ANACOSTIA, D. C.,
13 JUNE, 1928.

[17] Life of excited mercury atom. Wien: Ann. der Phys., *73*, p. 483; 1924.
[18] Mohler and Moore, J.O.S.A. & R.S.I., *15*, p. 74; 1927.
[19] Volkringer, Compt. Rend., *185*, p. 60; 1927.

THE PHOTOELECTRIC EFFECT IN GLOW-DISCHARGE TUBES

BY HERBERT J. REICH

The recent application of gas-filled glow-discharge tubes to rectification, voltage regulation, television, and to a number of useful instruments has brought this type of tube into the front rank of experimental investigation. Although most of the theoretical principles underlying its operation are well-known, there are a number of interesting phenomena connected with it which are not satisfactorily explained, and which therefore merit investigation.

The glow-discharge tube is a two-element tube, containing an inert gas at a pressure of about one to five millimeters. The electrodes may have any of a large variety of shapes and may be made of many kinds of metal. Their location and spacing, as well as the shape of the tube and the gas used, also vary over wide limits, depending upon the purpose for which the tube is designed. The gases ordinarily used are neon, helium, and argon.

If a low voltage is applied across the terminals of such a tube, and gradually increased, discharge will take place when the applied potential reaches a certain critical value, known as the sparking potential. An increase of applied voltage beyond this value results in a proportional increase of discharge current. When the applied voltage is again reduced, discharge does not cease at the sparking potential, but at a lower value, known as the extinction potential. To prevent arcing or excessive heating of the terminals when the applied voltage is too great, the current is usually limited by a high resistance in series with the tube. Because of the IR drop through the resistance, the terminal voltage during discharge is in this case less than the applied voltage.

The exact values of the sparking and extinction potentials depend upon the construction of the tube and electrodes, the kind of gas used, the gas pressure, and upon the operating conditions of the tube. If the tube is used in an oscillating circuit, so that discharge takes place periodically, the values of these critical potentials vary with the frequency. Many tubes are found to be affected in their behavior by external illumination, the sparking potential being lower when the tube is illuminated than when it is dark. It is this phenomenon in particular with which this paper will deal.

This phenomenon was first described by Oschwald and Tarrant[1] before the Physical Society of London in 1924. In their report they stated that they had discovered a new type of photoelectric effect having a maximum in the orange, that the seat of the effect was in the electrode surfaces, and that it was independent of the polarity of the electrode illuminated. It was pointed out, however, that they neglected to take into account the energy distribution of their source of light, and that this might readily account for the unusual location of the maximum. Mr. J. W. Ryde, in making this criticism,[1] stated that he had himself made a study of the phenomenon and believed it to be caused either by the presence of hydrogen in the gas or by a film on the surface of the electrodes. No subsequent paper on this subject having been published, it seemed worthwhile to undertake a further study of the phenomenon in order to determine, if possible, the underlying cause.

DESCRIPTION OF APPARATUS

The tubes used in the experiments which formed the basis of the present paper, chosen because of their high sensitiveness to illumination, were manufactured by Müller-Uri in Germany. They consisted of two

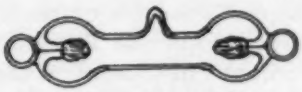

FIG. 1. *Glow tube (full size).*

glass bulbs about one centimeter in diameter, joined by a half-centimeter tube two centimeters long, filled with neon or with helium. (See Fig. 1.) The electrodes were small pieces of aluminum fused to glass projections within the bulbs.

As soon as a single sustained discharge took place in one of these tubes, the characteristics changed materially, so that different values of sparking potential were observed for subsequent discharges.[4] It was therefore impossible to study the effect of illumination on the sparking potential simply by increasing the applied voltage until discharge took place. This difficulty was overcome by the use of the so-called "neon-tube oscillator" circuit [2,3], shown in Fig. 2. The external capacity, C, or the capacity of the tube itself is charged by B - batteries through the

[1] Oschwald and Tarrant, Proc, Phys. Soc. Lond., *36*, pp. 241 and 262; 1924.
[2] Pearson and Anson, Proc. Phys. Soc. Lond., *34*, pp. 175 and 204; 1922.
[3] Taylor and Clarkson, Proc. Phys. Soc. Lond., *36*, p. 269; 1924.
[4] Taylor, J., Phil. Mag., *3*, pp. 368 and 753; 1927.

resistance of a saturated thermionic vacuum-tube. Discharge occurs as soon as the voltage across the terminals of the tube becomes equal to the sparking potential. The time of discharge is theoretically very short. The discharge current is the sum of that coming from the condenser and that which passes through the UX199 thermionic tube. Discharge ceases when the voltage has dropped to the extinction value, and the cycle then repeats. The theoretical voltage-time curve for the

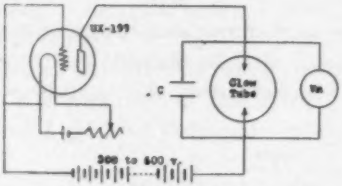

FIG. 2. *Glow tube circuit.*

terminal voltage is shown in Fig. 16. The frequency of discharge may be varied by changing either the external capacity or the filament current of the rectifier tube. By this means it was possible to obtain short-time discharges at regular intervals, and it was found that after about twenty minutes steady conditions were obtained.

The sparking potential, or peak terminal voltage, was measured by means of the vacuum-tube voltmeter shown in Fig. 3. The operation of this meter is as follows: With the switch, *S*, in position 1, the

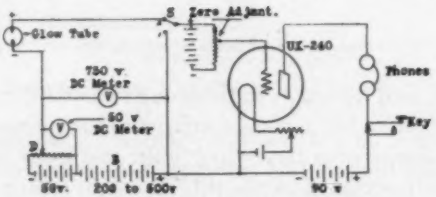

FIG. 3. *Vacuum tube voltmeter circuit.*

zero-adjustment bias is set so as to give zero plate current. This condition prevails when no click is heard in the phones when the key is opened and closed. This switch is then changed to position 2, and the additional biasing battery, *B*, and the voltage divider, *D*, adjusted so that the glow-tube oscillator tone just cannot be heard in the phones. The absence of the tone in the phones indicates that the grid at no time becomes more positive than it was for the initial adjustment with switch

S in position 1, and hence the added grid biasing voltage shown by the 750-volt *d. c.* meter must just equal and balance out the peak terminal voltage of the glow-tube. The 50-volt meter indicates more accurately small changes of sparking potential. This type of voltmeter draws no current when it is adjusted for a reading, and therefore has no effect upon the glow-tube except that due to its capacity, which remains constant. Voltage readings were taken with an accuracy of plus or minus 0.1 volt.

The source of light used throughout the experiments was a 500-watt street lamp of the single straight filament type, operated from a constant *d. c.* source. The light from this lamp passed through a single

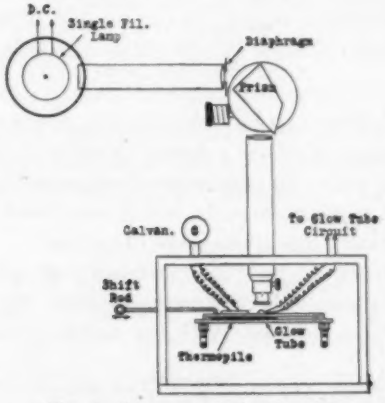

FIG. 4. *Arrangement of apparatus.*

monochromator, and thence directly through an exit slit to the tube, as shown in Fig. 4. In order to obtain sufficient illumination it was found necessary to dispense with the entrance slit and place the filament at the point normally occupied by the slit. The light falling upon the tube was not purely monochromatic, both because of the width of the filament and the exit slit, and because of scattered light, but it was found to be sufficiently so for the purpose. The use of a second monochromator was impossible because of the difficulty of obtaining a stronger source of light.

The intensity of the light falling upon the tube was measured by means of a thermopile. The thermopile and the tube were mounted on a movable slide so that either one could be brought into the path of the light at the same point without affecting the rest of the apparatus, thus

making it possible to obtain the energy distribution of the source during the run on the tube. The thermoelectric currents were measured by means of a high sensitivity d'Arsonval galvanometer.

EXPERIMENTAL PROCEDURE AND DISCUSSION OF CURVES

It soon became evident that the tubes were subject to a fatigue effect[4,5] which vitiated the results if too long a time elapsed during a single run, particularly if the tube was not new. Fig. 5, in which reduction of sparking potential with illumination has been plotted against light intensity, indicates this effect in tube #1, a neon-filled tube. The abscissas represent arbitrary units of light intensity, and the ordinates the actual reduction of sparking potential. In obtaining the data for

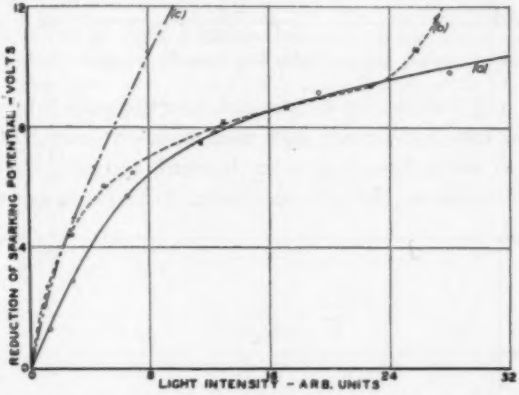

FIG. 5. *Reduction of sparking potential vs. light intensity tube No. 1 (before rejuvenation).*

these curves the relative intensity was carefully measured each time the intensity was increased, so that about half an hour elapsed during the run. Curves (*a*), (*b*), and (*c*) were plotted from three consecutive sets of data. It is evident that changes were taking place within the tube during the hour and a half during which these data were taken, particularly toward the end of the second run.

This discrepancy led to a study of the variation of sparking potential with time. Fig. 6 shows the variation of sparking potential with time for tube #1 without illumination. The drop in sparking potential during

[4] Watson, H. E., Proc. Chambr. Phil. Soc., 17, p. 90; 1912.
[5] Bedell and Reich, J.A.I.E.E., p. 563, June 1927.

the first two minutes, followed by subsequent increase to about the initial value seems to indicate that there is some sort of deposit on the surface of the electrodes which volatilizes and in so doing aids ionization. The supply is rapidly used up, so that the sparking potential

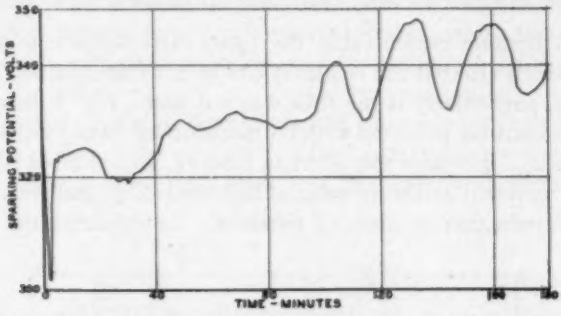

FIG. 6. *Variation of sparking potential with time tube No. 1—dark—(before rejuvenation).*

again rises. Fig. 7 shows the fatigue curve for the same tube with illumination. This tube had already been used for about forty hours previous to the time at which these data were obtained, and after the completion of the illuminated run the tube was found to be no longer sensitive to

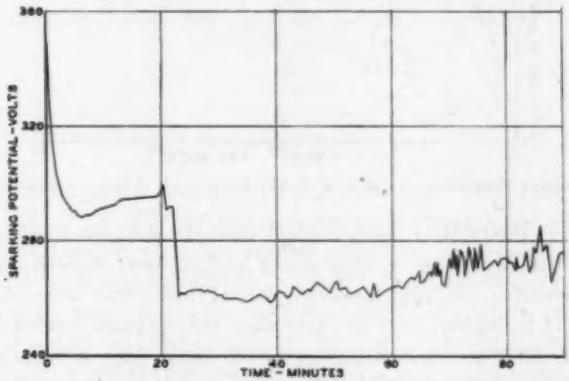

FIG. 7. *Variation of sparking potential with time tube No. 1—illuminated (before rejuvenation).*

light. An examination showed that the inner surface of the glass had become coated with metal from the electrodes, which now had a tarnished appearance. Whether the insensitiveness to light was caused by absorption of the light in passing through the deposit on the glass or by

a change in the electrodes could not be determined. After about a week's rest the tube was again tested and found to be sensitive to light for a few minutes of operation, after which it again became insensitive. The tube was later carefully heated to drive the deposit off the glass. It was then found to be quite as sensitive as when it was new, but the sparking potential had risen from about 340 volts to 500 volts, possibly because of some change in the gas or the electrode surfaces. After the heat treatment the sparking potential time curves were found to be similar to those obtained with a new tube.

The variations of sparking potential with time in tube #1 before rejuvenation were very much greater than those subsequently observed in other tubes which had not been used for so long a time. It is probable that these large changes were associated with disappearance of light sensitivity, due to some change in the structure of the electrode surfaces incident to sputtering. Figs. 8 and 9 are sparking potential-time curves

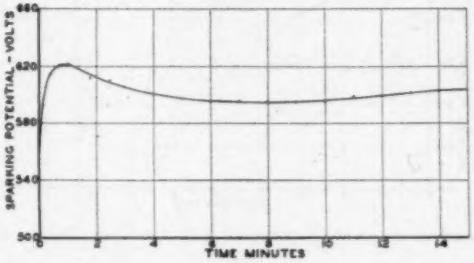

FIG. 8. *Variation of sparking potential with time tube No. 2—dark.*

for tube #2, a new helium-filled tube. The curves are seen to be much smoother than those for tube #1. It was found that after about twenty minutes, steady values of both dark and illuminated sparking potential were obtained. After the tube had been used for a few hours the dark sparking potential was found to drop and rise during the first minute, in the manner observed in tube #1 (Fig. 6).

The rise in sparking potential with successive discharges has been observed by a number of experimenters and was studied in considerable detail by J. Taylor in 1927.[4] Taylor attributed the rise of sparking potential to polarized layers of gas on the electrodes, principally a positively charged layer on the cathode, which reduced the effective potential drop between the electrodes, and also possibly ended to reduce any photoelectric action on the surface of the cathode. This

theory explains the initial increase of sparking potential observed in tube #2 during the first minute of operation without illumination (Fig. 8), but does not explain the subsequent decrease. It also fails to explain the rapid decrease of sparking potential observed in tube #1, and other tubes which had been used for a few hours, during the first minute of operation without illumination, or the decrease in illuminated sparking potential with time in tube #1 (Fig. 9). As will be shown a little later, the results of experiments on these tubes indicate that the change in sparking potential with illumination is caused by photoelectric action. If this is so, then according to Taylor's theory this effect should decrease with time due to the reduction of photoelectric action by the polarization, and hence the illuminated sparking potential should rise with time, rather than fall. It therefore seems likely that in addition to polarization there is another action, such as vaporization of some sub-

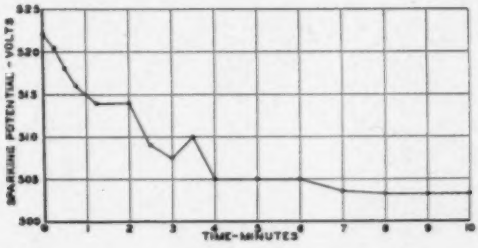

FIG. 9. *Variation of sparking potential with time tube No. 2—illuminated.*

stance on the electrodes or walls of the tube, which produces the opposite effect.

In order to reduce the time taken for runs in which the intensity was varied, a series of eleven graded diaphragms was made, and their relative transmission measured. The use of these diaphragms made possible the taking of a set of observations in about five minutes instead of thirty, thus reducing the possibility of variation of characteristics during the run.

Fig. 10 shows the change in sparking potential with illumination of tube #2. The four curves show the effect of fatigue in the tube, the upper three being for consecutive runs made just after the tube was started, and the lower one for a run made after half an hour of operation. The fatigue action was confined to the first twenty minutes of operation, and no further change was observed after that. Inasmuch as the illuminated sparking potential drops with time, the reduction of light effect

with time cannot be explained on the basis of Taylor's theory. The reduction of light effect is to be expected from a consideration of Figs. 8 and 9, since after the dark sparking potential reaches its maximum at the end of a minute, there is a drop of over twenty volts in the dark potential during the succeeding ten minutes, and only about eleven volts in the illuminated sparking potential.

Fig. 10 also shows that the change in sparking potential per unit of light intensity is less for high than for low intensities. This is explained by two factors. First, it is impossible to reduce the sparking potential below a certain minimum value, since some fall of potential is necessary

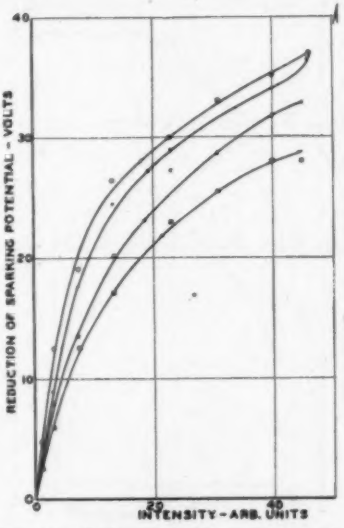

FIG. 10. *Fatigue tube No. 2—120 cycles*

at the cathode in order to maintain discharge. Secondly, we should expect that ions produced during one discharge would tend to accumulate on the walls of the tube and thus remain for some time after the cessation of discharge before drifting off and recombining. (That a charge actually does collect on the inner walls of the tube is demonstrated by the fact that a charge collects on the outer walls of the tube during discharge. The presence of a small amount of moisture in the air surrounding the tube, produced by blowing on the tube or bringing the hand near it, changes this charge and produces a very noticeable change in the sparking potential and the frequency of discharge. This is not a

hand capacity effect, since placing a piece of paper between the hand and the tube stops the action.) The light effect is undoubtedly associated with ionization, and ionization persisting from a previous discharge at the time of discharge would tend to reduce the relative effect produced by the light. The frequency of oscillation is dependent upon the potential range through which the condenser charges, and hence upon the sparking potential. Since the light decreases the sparking potential, it increases the frequency. The higher the discharge frequency, the shorter is the interval between discharges, and so the greater the possi-

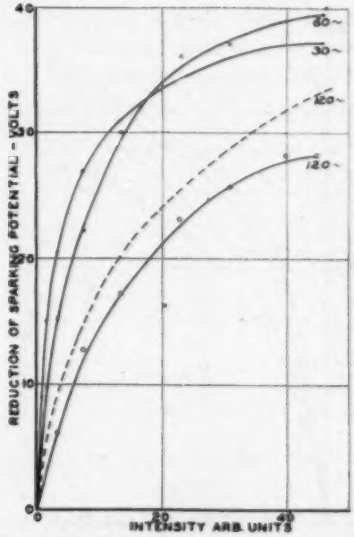

FIG 11. *Reduction of sparking potential vs. light intensity showing effect of frequency variation tube No. 2.*

bility of the holding over of ionization between discharges. That this theory is essentially correct seems to be proved by Figs. 11 and 12, in which change in sparking potential with illumination has been plotted against light intensity for different values of frequency. The effect of the light is greater at lower frequencies. The dotted line in Fig. 11 is for a run taken before the tube had assumed steady conditions. The data for Fig. 12 were obtained from tube #1 after the deposit had been driven off by heating. The crossing of the 60 and 30 cycle curves in Fig. 11 will be discussed later.

Curves similar to those of Fig. 12 were obtained when the capacity across the tube was varied for a given value of frequency. The light effect decreased with an increase of capacity. This is probably explained by the fact that the larger the capacity, the greater must be the current in the tube during discharge, and hence the greater the persistence of ionization between discharges.

There seemed to be no definite relation between the portion of the tube illuminated and the magnitude of the light effect. The point of maximum sensitivity varied from tube to tube, and frequently appeared

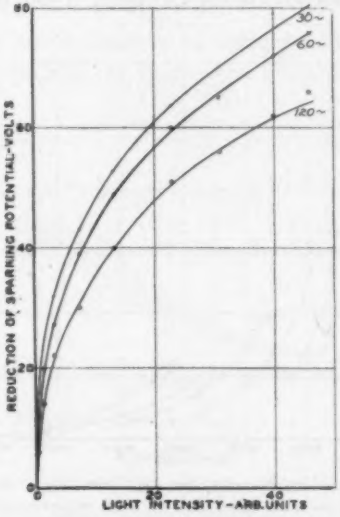

FIG. 12. *Reduction of sparking potential vs. light intensity tube No. 1 (after rejuvenation).*

to be on the glass rather than on the electrodes. In some tubes the effect was greater on the cathode than on the anode, and in others vice versa. The effect was usually found to be greater when discharge was in one direction than when it was in the other, and seemed to be greatest just after reversal, with subsequent fatigue.[4] In tests on other types of tubes it was found that in tubes having large electrodes in which the discharge for low currents covered only a small part of the electrodes, the greatest light effect was observed when the light was allowed to fall upon that portion of the cathode at which discharge occurred.

Since the relation between change in sparking potential and light intensity is not linear it was impossible to study the effect of varying the wave length of the light for constant intensity by keeping the source constant and making use of the energy distribution curve to correct for the uneven energy distribution. Because of the length of time necessary to adjust the source so as to give exactly the same intensity at the tube for various wave lengths, it was also found unsatisfactory to compensate for the varying energy by changing the intensity at the lamp. It was consequently necessary to employ an indirect method. The various diaphragms were used in succession in obtaining readings over small overlapping portions of the spectrum. From these readings curves

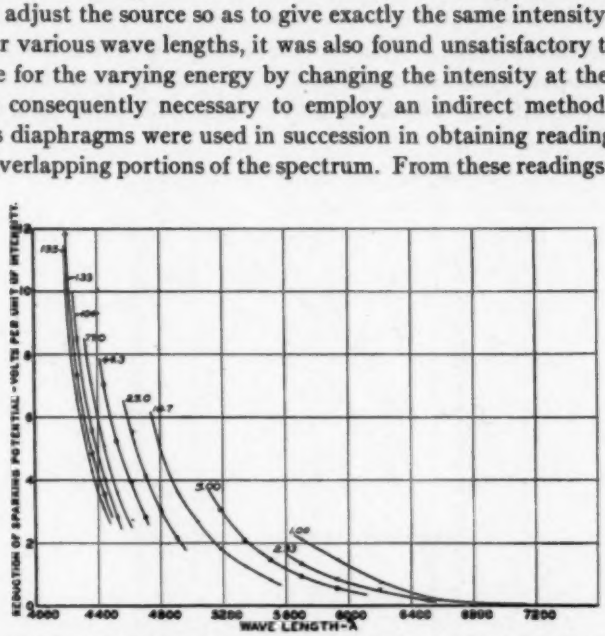

FIG. 13. *Reduction of sparking potential per unit intensity vs. light intensity, for various diaphragms tube No. 1 (after rejuvenation).*

were plotted showing the variation of change in sparking potential per arbitrary unit of light intensity with wave length of the light, as shown in Fig. 13. The numbers at the left ends of the curves give the relative transmission of the diaphragms. Since the effect is relatively greater for lower intensities, and since the intensity decreases toward the blue end of the spectrum, the curve for each diaphragm has too great a slope, and the curves do not join. By picking out points on the various curves which have the same value of arbitrary intensity, however, it is possible to obtain a series of points which will give the correct characteristic wave length curve for that arbitrary value of intensity. This may readily be done as the relative transmission of the diaphragms is

known, and the energy distribution of the source was obtained just before the run was started. Thus, for an arbitrary intensity of 100 it is necessary to find wave lengths such that the product of the transmission of the diaphragms by the intensity of the light is equal to 100 arbitrary units. For the smallest diaphragm, for which the transmission was taken as unity, the intensity of the source must be 100; for the second, having a transmission of 2.33, it must be $100/2.33 = 42.9$; for the third it must be $100/5 = 20$; etc. The energy distribution curve readily gives the wave lengths having these relative intensities, and the wave length indicated for each diaphragm may be used in choosing corresponding points from the curves of Fig. 13.

Fig. 14 shows the curves obtained by this method with tube #1. The numbers at the left ends of the curves give the values of arbitrary in-

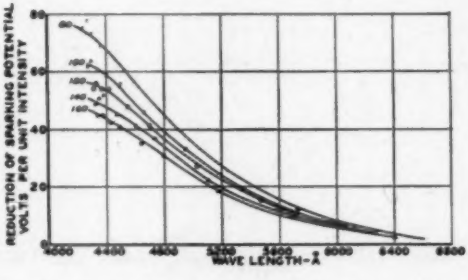

FIG. 14. *Wavelength characteristic tube No. 1—30 cycles*

tensity. It is evident that the curves are of the type obtained for the ordinary photo-electric effect, the rounding off at the long wave length end being explained by scattering and by the fact that the source and the exit slit were fairly wide. Fig. 15 gives similar curves for tube #2. Prolongation of the straight portions of the curves gives a long wave length cutoff of between 5600 and 5800 Ängstrom units for tube #1 and between 6000 and 6100 Ängstrom units for tube #2. The value found for the sodium photo-electric cutoff by Millikan in 1916 is 6800,[7] and by Richardson and Compton in 1912, 5830.[8] Because of the difficulty of obtaining a stronger source of light of shorter wave length and the danger of absorption by the glass walls of the tubes at lower wave

[7] Millikan, R. A., Phys. Rev., *7*, No. 3, p. 386; 1916.
[8] Richardson and Compton, Phil. Mag., *24*, p. 575; 1912.

lengths, no attempt was made to locate the maxima. The accuracy possible in these experiments is not sufficiently great to justify the conclusion that the curves obtained are really photo-electric curves for sodium, but they strongly suggest this possibility.

Upon the completion of these experiments a spectroscopic study was made of the tubes in an attempt to determine whether the tubes contained any alkali metals. This was first done by connecting them to a large electrostatic machine, which produced such an intense discharge that a blue ionization glow was plainly visible. Direct comparison with the spectrum of sodium by means of a spectroscope and comparison prism very clearly disclosed the sodium *D* lines. A subsequent spectrograph obtained from pieces of the terminals and of the glass showed a trace of sodium and a very minute trace of lithium. It was later learned from the makers that these tubes had been evacuated by pumps which

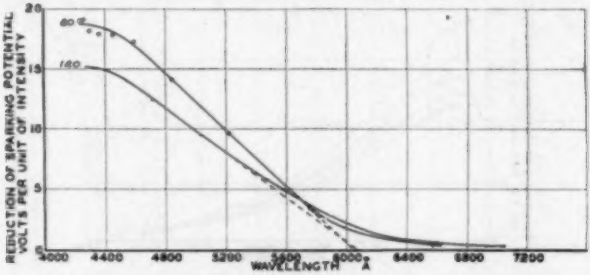

FIG. 15. *Wavelength characteristic tube No. 2—120 cycles*

had previously been used for evacuating indicator tubes containing a charge of sodium. These facts lend strength to the assumption that the light effect is a true photo-electric effect produced by the presence of small amounts of sodium within the tubes.

Whether or not this type of tube will have a practical application if developed to the utmost sensitivity still remains to be seen. With the tubes used in these experiments it was possible to operate a relay and thus sound an alarm when a match was lighted seven or eight feet away. If the effect is really produced by sodium, then it should be possible to increase the sensitivity to a very useful point by the deliberate introduction of this metal.

OTHER PHENOMENA OBSERVED DURING THE EXPERIMENTS

Several interesting phenomena were observed during the course of these experiments. After the tubes had been used for fifteen or twenty

hours an increase of intensity when the tube was oscillating at a low frequency produced for certain intensities an abrupt increase of sparking potential, rather than a decrease. This is illustrated in Fig. 16, in which sparking potential has been plotted against light intensity. An increase of intensity results in a decrease of sparking potential until point *A* is reached, when there is an abrupt increase. Further increase of intensity again decreases the sparking potential until point *B* is reached, when there is another sudden increase. Under certain conditions as many as three of these discontinuities were found. When the intensity was again decreased the breaks occurred at lower intensities than when it was being increased, as shown in Fig. 16 by dotted lines. For frequencies higher than about 45 cycles this effect could not be produced. It was

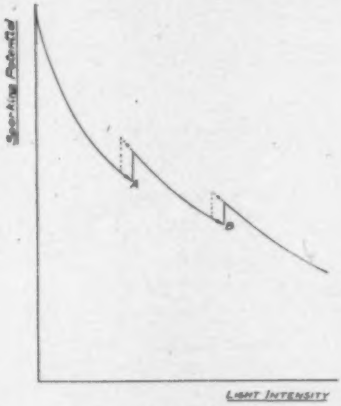

FIG. 16.

observed in tube #1 just before it became insensitive to light, and still persisted just after rejuvenation. After a few minutes of use the tube then again became normal in this respect. The crossing of the 60 and 30 cycle curves in Fig. 11 is probably the result of the same cause. This effect was not observed in any other type of tubes, and no adequate explanation has yet been found.

In order to determine whether the light produced any change in the voltage wave form of these tubes the wave forms were studied by means of the Burt Stabilized Oscilloscope,[6] which gives a stationary picture of the wave plotted on a time base. Sketches of the wave forms for tube #2 are shown in Fig. 17. The wave forms for other tubes of the same type differed in minor respects, but were in the main similar. The

reduction in sparking potential with illumination reduces the amplitude of the curve, and since the frequency also increases, the wave length is reduced. The interesting thing here to be observed is that the actual wave forms do not agree with the theoretical. Instead of dropping directly to the extinction potential during discharge, the voltage drops to a value slightly higher, and then decays gradually. More than half the period of oscillation is taken up by the time of this decay. Several investigators have developed theoretical expressions for the time of discharge and the period of the cycle on the assumption either that resistance of the tube remains constant throughout discharge or that it is a linear function of the terminal voltage.[2,3] These derivations show that the time of discharge should theoretically take up about 1% or less, of

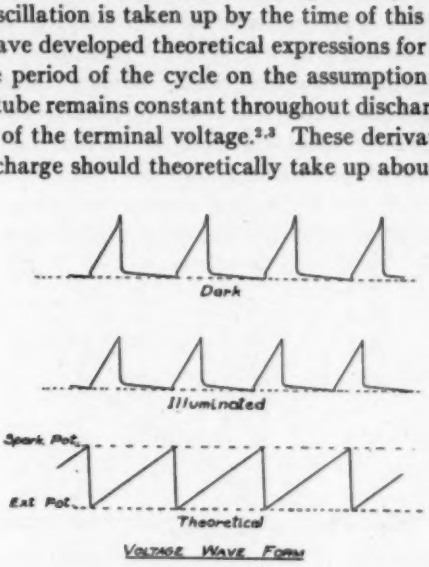

FIG. 17.

the complete period, and that the voltage should decrease according to an exponential function of the time. It is clear that these derivations will not apply to this type of tube, and that the wave form of any tube must be studied before they can be applied to it. The sudden reduction of the rate of discharge shown in oscillograms of Fig. 17 is probably caused by an abrupt change in the resistance of the tube, but it is not at all evident why this change should occur. Other types of tubes were found to have the theoretical wave form. These results emphasize the necessity of a careful examination of the wave form of any glow discharge tube used in obtaining a linear time axis in oscillograph work, as in the Burt Oscilloscope.

It was also found during the course of this work that the sparking potential could be controlled to a considerable extent by the charge

induced on the surface of the glass. This charge was varied by means of wire or tinfoil wrapped around the outside of the tube and connected to various parts of the circuit, either directly or through a high resistance. The applied voltage could be adjusted so that discharge occurred only when this shield or external grid was connected to one of the electrodes. This phenomenon is similar to that observed in the Knowles Grid-glow Tube, and can without doubt be used for similar purposes. When the output of a radio set was connected between the shield and one electrode, and the voltage applied across the electrodes properly adjusted, discharge took place in response to the higher amplitudes of the receiver output.

SUMMARY

The results of these experiments indicate that:

1. The light effect observed in these tubes is a true photoelectric effect produced by the presence of small amounts of alkali metals on the electrodes and walls. These experiments do not necessarily prove that the light effects observed by Oschwald and Tarrant and by Ryde were due to the same cause, but the probability is that the latter were similar to those here described. This question can be fully answered only after a thorough study of tubes made specially for the purpose.

2. When the tubes are used in an oscillating circuit, the reduction of sparking potential with illumination is not proportional to light intensity, the reduction per unit of intensity being less for high than for low intensities.

3. There is no definite relation between the portion of the tube illuminated and the magnitude of the effect.

4. In addition to the polarizing action studied by Taylor, which tends to raise the sparking potential in successive discharges, there seems to be in this type of tube another action producing the opposite effect.

5. In tubes which have been used for quite a few hours, when the tube is oscillating at frequencies below about 45 cycles, an increase of intensity will at certain intensities produce an abrupt increase of sparking potential rather than the normal decrease.

6. The voltage-time wave form is not that which would be theoretically expected. The terminal voltage does not fall according to an exponential function of the time during discharge, the rate of discharge suddenly dropping to a much lower value shortly before the extinction potential is reached. The time of discharge takes up more than half the

complete cycle, instead of about 1% or less, as theoretically predicted, and as observed in other types of tubes. This points out the necessity of studying the wave form of any glow-discharge tube before applying theoretical equations to it, or before using it in obtaining a linear time axis in oscillograph work.

7. Discharge can be controlled by means of an external shield or grid connected to various parts of the circuit, either directly or through a high resistance.

No satisfactory explanantion presents itself for some of the phenomena observed, nor for some of the seeming disagreements with the results of earlier experiments. It is hoped that the experiments now in progress in this and in other laboratories will afford complete solutions to these problems.

A complete list of references covering the theory of the glow-discharge tube and its application in oscillograph work, will be found in the sixth reference.

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ITHACA, NEW YORK

THE X-RAY PHOSPHORESCENT AND THERMOPHOSPHORESCENT RADIATIONS OF KUNZITE

By Otto Stuhlman, Jr. and A. F. Daniel

Kunzite is a variety of pink spodumene, found in California, a $Li(SiO_3)_2$ containing about 7% lithium.[1] A brittle monoclinic crystal of 6.5 to 7.0 hardness and specific gravity 3.13 to 3.20. It possesses a vitreous lustre and if observed transversely varies from the palest shade of pink to a deep lilac tint. These colors are attributed to its 11% mangenese content.[2]

Pochettino[3] in subjecting the crystal to cathode ray bombardment, found that the spectrum of the phosphorescent emission consisted of a strong band extending from .690 to .515μ and a weak band from .480 to .420μ. Nichols and Howes[3] verified the existence of these two bands and in a detailed study showed that the stronger band extended from .5 to .7μ. Their spectrophotometric measurements showed a distribution of intensities nearly symmetrical but with a more aburpt rise at the short wave length end. A well defined maximum was found to exist at .590μ, but nothing to suggest that it was a composite of overlapping bands. The weaker band was shown by them to begin at .49μ and extend to .40μ with its maximum at approximately .432μ.

Both Kunz and Baskerville[4,5,6] exposed kunzite to radium and x-radiation. After prolonged exposure to these radiations the crystals showed very marked changes in color, emitting an intense phosphorescent orange-pink light. Lind and Bardwell,[7] after exposing kunzite to x-radiation, observed that the original lilac tint gradually vanished and the crystal became colorless. Upon prolonged radiation the kunzite gradually changed to a green and finally to a blue-green shade.

X-RAY PHOSPHORESCENCE

The first part of these experiments consisted in determining the spectral distribution of the phosphorescence excited in kunzite crystals by general x-radiation.

[1] Davis, Amer. J. Soc., *8*, 29; 1904.
[2] Pochettino, Il Nuovo Cimento, *18*, p. 245; 1909; *1*, p. 21; 1911.
[3] Nichols and Howes, P. R., p. 18; 1914.
[4] G. F. Kunz, Sc., *18*, p. 280; 1903.
[5] Baskerville, Sc., *18* p. 303; 1903., Sc., *18*, p. 769; 1903.
[6] Baskerville and Kunz. Amer. J. Sc , *18*, p. 25; 1904.
[7] Lind and Bardwell. J. Franklin Inst., *196*, p. 375; 1923.

The color of this phosphorescent light was so similar to the cathode-phosphorescence of kunzite described by Nichols and Howes[3] and to the radium excited phosphorescence described by Lind and Bardwell[10] that the x-ray phosphorescent emission was suspected to possess the same spectral distribution as the two proceeding emissions.

Samples of kunzite were exposed to unfiltered x-radiation from a tungsten target Coolidge tube, operated at about 50,000 volts and 20 m.a. The resulting fluorescence was then examined through a series of Wallace color filters to determine the general nature of the emission. This visual examination resulted in separating the emission into a strong orange-red and a faint blue-green band. The orange band was found to extend approximately from .5μ to .7μ with a maximum near .58μ. The fainter blue-green band was identified as possessing a maximum near .48μ.

A larger pale lilac crystal was next fractured so as to produce similar halves. One of these was then exposed to the above x-radiation for a period of four hours. The crystal was found gradually to discolor during exposure, changing to various shades of green and finally to the deep blue-green color observed by others.[7,10] The half thus radiated, phosphoresced with the characteristic colors originally described by Kunz[4] and Baskerville.[5,6] The unrayed half showed no visible emission. The two halves of the crystal were then placed for 24 hours in contact with a panchromatic plate to make a comparative test of their actinic properties. The unrayed half produced no effect on the plate whatever while the x-rayed half formed an opaque image on it. The activated half was next placed so that one-third of its surface was in direct contact with the sensitized side of a panchromatic plate; another third was screened by a microscope slide of 1 mm thickness, with a limiting transparency of .31μ; and the remaining third by a single layer of black photographic paper. After a 24 hour exposure it was discovered that the black paper was opaque to the phosphorescent emission, while the third, screened by the glass, possessed the same photographic density as the unscreened third. Thus excluding ultraviolet light of wave length less than .31μ from these x-ray phosphorescent radiations.

A series of contact photographs through color filters of known spectral transparency, were next made by placing an x-rayed crystal for a period of one minute on a panchromatic plate. A study of the comparative photographic blackening indicated the presence of two emission bands. The weak blue-green one, identified visually, was located with its maximum at approximately .50μ and the orange-red band with a steeper

intensity slope on its short wave length side was placed with its maximum at about .65μ.

The similarity between these values and those for the cathodophosphorescent bands measured by Nichols and Howes[3] led us to a more detailed study of the radiation. The x-ray phosphorescent emission was next photographed with a Gaertner spectrograph. The absorption of the prism beyond .43μ, which was well over 50%, did not allow us to record the weaker blue-green band.

For this study a kunzite crystal 7 mm in thickness was fastened to the slit of the spectrograph. The instrument was placed in a lead lined box with the crystal and slit protruding through a small opening. To insure against the admission of stray light from the filament of the Coolidge tube, a black photographic paper hood was placed over the crystal and slit. The crystal was then excited by exposing it to the x-radiation for 15 sec. (300 m.a. sec.) with a 45 sec. rest period. A total exposure of two hours produced a recognizable continuous spectrum on a panchromatic plate. A comparison neon spectrum photographed above and below it showed the continuous spectrum to extend from .65μ to .57μ with a well defined maximum at .596μ.

The cathodophosphorescent band found by Nichols and Howes[3] extending over the same range with its maximum at .590μ proves that the phosphorescent emissions of kunzite are practically identical. This would be expected if we attribute the phosphorescence to the x-ray radiation generated by the bombarding cathode stream rather than to the cathode stream itself.

The period of decay of the phosphorescence is very long. A succession of panchromatic plates, exposed for 24 hours at 24 hour intervals, in contact with an activated crystal showed that the threshold value of the plate had been reached only after a 76 hour rest period.

This is of interest to the manufacturer of x-ray intensifying screens. Despite its unusual x-ray phosphorescent brilliancy, this lag renders impracticable the use of powdered kunzite crystals in the manufacture of intensifying screens for medical radiological work.

THERMOPHOSPHORESCENCE

The thermophosphorescence of kunzite was originally observed and described by its discoverer[6] as a yellow-orange glow. Pochettino[2] showed that the emission set in at 235°C, decreasing in intensity with increase in temperature and disappeared at 400°C. He found however, that the ability to emit light did not change.

The samples examined by us did not fulfill the specifications quantitatively. We found, for example, that our specimens began emitting a rose colored light at about 168°C. Spectrograms were not obtainable because of the low intensity of the emitted energy. When the light was examined through a series of color filters, it was found to be composed of a broad orange-red band with a marked maximum near .64μ accompanied by a weaker emission band around .50μ. As the temperature was gradually increased to 400°C, the bands gradually widened until at 400° the phosphorescence suddenly ceased. At this temperature the phosphorescence attained its maximum intensity and was observed to be nearly colorless. Heating to higher temperatures, up to the fusion point of the crystal, produced no additional thermoluminescent emission.

Upon examining the recently heated crystal at room temperature it was found that the blue-green color produced by x-radiations had disappeared. The crystal was perfectly transparent and colorless. Further cooling did not restore the color of any of the crystals examined. Subjecting the kunzite to additional x-radiation repeatedly built up the final or saturated blue-green color. It successively passed through the intermediate shades of lilac, then through a colorless stage presumably by the addition of a green component to the lilac, to saturate eventually by the addition of blue to its final blue-green color. At no time did the color of this final stage approach the yellow-green of hiddenite, to which it has often been compared. This cycle can apparently be repeated indefinitely.

Heating does not drive off water of crystallization. If existing at all it must be present in less than one part in 30,000, since careful weighing showed no loss greater than this amount.

The change in color due to heating, or the inverse effect, the formation of a colorless crystal through stages of red, blue-red, white, green to blue-green as a result of irradiation by ultraviolet light, x-ray, or radium radiations, can approximately be accounted for on an oxidation and reduction hypothesis.

For instance, Kantsky and Zocher[8] and Kantsky and Neitzke[9] experimenting with a silicon compound in solution, of approximate $Si_6O_3H_6$ composition, found that when it was oxidized by $KMnO_4$, the solution emitted light. When examined spectrographically the emission was found to consist of a band with a maximum at .582μ.

[8] Kantsky and Zocher, ZS. f. Phys., *9*, p. 267; 1922.
[9] Kantsky and Neitzke, ZS. f. Phys., *31*, p. 60; 1925.

If we suppose the final blue-green crystal of kunzite to be a solid solution containing a silicon compound, as analysis has shown with Mn(.11%) and K(.06%)[8] present in the form of $KMnO_4$, to be used in the oxidation of the silicon compound, the first colorless stage might then be considered as being obtained by the use of some of the available oxygen from the $KMnO_4$ in connection with the rise in temperature and a subsequent oxidation of the silicon compound. The loss of an oxygen atom from $KMnO_4$ would result in a change in color from blue-green to white with the introduction of red by the lower oxides of the manganese as the result of splitting off successive oxygen atoms. Upon further heating to higher temperatures the intermediate oxide forms of manganese become more and more predominant with the addition of more red so that the color gradually changes to lilac. Finally near 400°C the lower forms, Mn and MnO with their predominant green colors, produce a compensating effect resulting once more in a colorless stage of greater stability. This process is of course reversible through the excitation of the molecules by x-ray or radium radiations.

Hence it follows that the luminescent radiations of kunzite are independent of the method by which they are produced and are only dependent on the reaction between the solvent and solute participating in the chemical reaction with the emission of chemiluminescent radiations.

THE UNIVERSITY OF NORTH CAROLINA,
DEPARTMENT OF PHYSICS,
CHAPEL HILL, N. C.

The Brown Instrument Company builds new plant addition. The Brown Instrument Company of Philadelphia, makers of industrial and power plant indicating, recording and automatic control instruments for measuring temperature, pressure, fluid, flow, machine speed, per cent CO_2 in furnace flue gases, etc., is building another addition to its plant. The new structure will be 60 ft long by 44 ft deep and two stories in height. Heavy foundations will permit other floors to be added as future requirements may demand. Construction will be strictly fireproof throughout. The rapid growth of the company and the enlargement of its line has made necessary this latest plant addition, the third within eight years. Its primary purpose is to provide research facilities commensurate with the needs imposed by the rapid expansion of the company's interests with respect to variety of products and the continually widening application of Brown Instruments to the activities of industry and science.

INSTRUMENT SECTION

A SONIC INTERFEROMETER FOR MEASURING COMPRESSIONAL VELOCITIES IN LIQUIDS: A PRECISION METHOD[1]

By A. L. Loomis and J. C. Hubbard

INTRODUCTION

The following paper describes an instrument developed by the authors, together with methods of its operation for the precise determination of the velocity of high frequency compressional waves in liquids. The precision attainable is such that the instrument promises to be a valuable tool of research both for the empirical analysis of liquids, and for the study of their thermodynamic properties We have measured such velocities at various temperatures in water, mercury, a number of salt solutions, and in certain organic liquids. From the results for water and mercury we have computed the values of a number of their thermodynamic properties which have been found to be in excellent agreement with those obtained from Bridgman's compressibility measurements.[2]

The method of measuring the velocity of sound "by resonance," i.e., by a study of the system of standing waves produced in a column of fluid by a source of constant frequency is, of course, an old one. It has recently been brought to a beautiful degree of precision for gases by Pierce,[3] whose experiments on the velocity of sound in air and in CO_2 are well known.

With liquids, however, none of the methods hitherto used gives, in the hands of different observers, consistent results. This is because audible frequencies have been used, producing wave lengths in the liquid which are large compared with the diameter of the liquid column. Under these conditions the elastic reaction of the walls of the chamber containing the liquid modifies the wave length so that complicated correction of large magnitude must be made.

[1] Communication No. 5 from the Loomis Laboratories, Tuxedo Park, N. Y.

[2] J. C. Hubbard and A. L. Loomis, Nature, *120*, p. 189; Aug. 6, 1927; Phys. Rev., *31*, p. 158; 1928 (abstract); Phil. Mag.. *5*, pp. 1177–1190; June, 1928.

[3] G. W. Pierce, Proc. Am. Acad., *60*, pp. 269–302; 1925.

Langevin[4] first showed how a piezo-electric plate could be driven by a source of alternating potential so as to produce compressional waves in water. R. W. Wood and A. L. Loomis[5] have carried out extensive experiments on the effects of high frequency compressional waves in liquids. They used a large disc of quartz immersed in oil and driven at high frequencies by an independent oscillator. They have recorded a number of phenomena due to the production of standing waves in the oil when a reflecting surface is held in the oil parallel to the quartz disc. It was these experiments which suggested the development described in the present paper. We have used frequencies such that the wave length in the liquid is small compared with the diameter of the vibrating quartz plate, and it is found that under this condition the measured value of the velocity in the liquid is independent to a very high degree of precision of the dimensions and material of the containing vessel.

THE SONIC INTERFEROMETER

We use as a source of vibrations in the liquid a circular piezo-electic quartz plate, about 50 mm in diameter and 6 mm in thickness. Since in the frequency limits within which we have worked, we have found no evidence of a variation of velocity with frequency, we have found it convenient to drive the crystal at exactly 500,000 cycles/sec., for the velocity of sound in meters/sec. then has the same numerical value as the half wave length in the liquid in thousandths of a mm, and can, therefore, be read directly from the screw[6] which is used to measure the wave length.

One face of the quartz plate is in contact with a thin metal diaphragm which bounds one end of the liquid column. The other face of the plate is in contact with an electrode which is connected to an oscillating electrical circuit. The length of the liquid column in which the standing waves are produced is varied by means of a micrometer screw which displaces either a piston or a chamber containing the vibrating quartz plate. Two principle forms of apparatus have been developed, photographs of which are reproduced in Fig. 1. One type of instrument is shown in diagram in Fig. 2. A metal cylinder C is closed at its lower end by a stiff metal plate, accurately plane and

[4] Langevin, Brit. Pat. Spec., N. S. No. 145691, p. 457; 1920.

[5] R. W. Wood and A. L. Loomis, Phil. Mag., *4*, pp. 417–436; 1927.

[6] Let u be velocity of sound in cm/sec., λ the wave length in the liquid in cm, then $u = n\lambda = 500{,}000 \times 2 \times \lambda/2 = 10^6 \times \lambda/2$. Or, $u = \lambda/2$ if u is in m/sec., and λ in meters $\times 10^{-6}$.

perpendicular to the axis of the cylinder. The plate is set into the cylinder at a sufficient distance so that a cushion of air is formed below it when the instrument is placed in a thermostat. Within the cylinder is a chamber D, consisting of a cylindrical cell of metal, closed at the bottom by a thin stretched metal diaphragm. On the diaphragm rests the piezo-electric plate, Q, a few drops of oil being put on the diaphragm before the plate is placed in position. The cylinder and the inner chamber are grounded, the diaphragm thus serves as the grounded electrode of the quartz plate. On top of the quartz plate, is a thin disc of metal to which connection is made by the wire L passing up through a vent in the cover of the chamber, and making connection with a point on an oscillating circuit, the cover being soldered on after the quartz

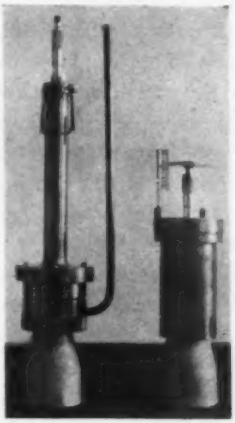

FIG. 1. *Photograph of two types of sonic interferometer.*

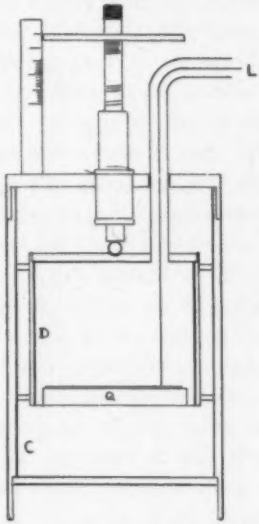

FIG. 2. *Sonic interferometer. Moving crystal type.*

plate and upper diaphragm are placed in position. In the center of the cover of the chamber D is a conical cavity in which rests a 3/16 inch steel ball. The cover of the main cylinder supports a micrometer screw which bears upon the ball. The liquid to be studied is placed in the cylinder C, the chamber D is then inserted, and the cover of the outer cylinder is put on. The inner chamber is provided with projecting rings which are accurately ground to fit the outer cylinder, the rings

being pierced by a number of small holes to permit displacement of the liquid when the chamber is moved by turning the screw. An external spring is attached by a clip to the pipe shielding the lead *L*, and supported from above so as to maintain a uniform pressure between the end of the screw and the steel ball. All joints except that between the main cylinder and its cover are soldered. The interior of the cylinder *C*, and the exterior of the inner chamber *D* should be heavily gold plated. The inner chamber should be made of steel, and the diaphragm of

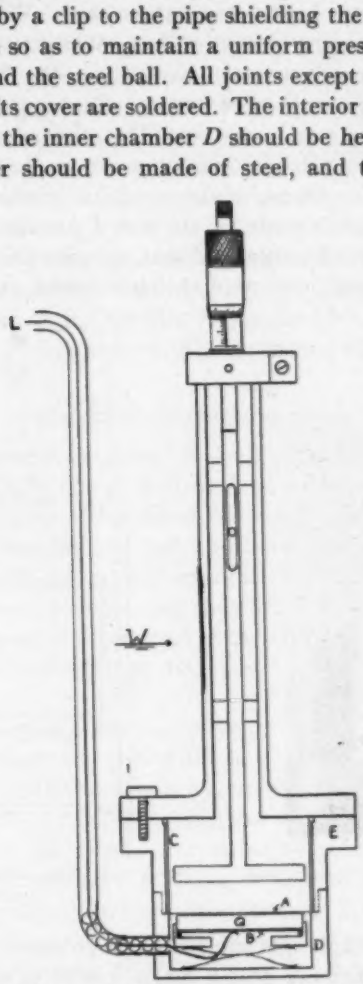

FIG. 3. *Sonic interferometer for deep immersion in a thermostat, stationary crystal.*

phosphor-bronze, as after soldering the greater shrinkage of the latter metal ensures a taut diaphragm.

The second instrument is shown in Fig. 3. It has been designed especially for immersion in a thermostat and for low loss of vapor

from the liquid under investigation. The thin walled steel cylinder *C* fits into the massive cylinder *E* of bronze. The lower end of cylinder *C* is closed by a taut diaphragm *A*, of phosphor-bronze. Cylinder *C* and diaphragm thus form a cup 2 1/4 inches in diameter, and 1 1/2 inches deep, easily removable for cleaning. The cap *D* screws on the lower end of cylinder *E*, enclosing a space containing the piezo-electric quartz disc and its mounting. The mounting is arranged so that when the cap *D* is screwed into place, the quartz disc *Q* makes contact with the diaphragm *A*, which serves as the grounded electrode of the quartz. The mounting of the quartz consists of the diaphragm *B*, attached to a brass ring supported in a bakelite cup, the latter resting upon a very light spring made from a circular sheet of phosphor-bronze or spring brass.[7] The electrode *B* is connected through the shielded lead *L* to the source of oscillating potential. The tube shielding *L* also serves as a vent for the chamber *D* so as to maintain atmospheric pressure in the chamber. The liquid to be studied is put into the cell, *C*, after which the cover supporting the piston and micrometer screw is placed in position and secured with six large screws. The piston rod travels through two guide rings in the tube surmounting the cover, the lower guide ring being elevated above the lower end of the tube to avoid being wet by the liquid in the cell as the piston rod is raised. The tube is slotted to take a pin passing through the piston rod and small springs or rubber bands attached to the pin are supported from above from pins in the top of the tube, maintaining a firm pressure between the end of the rod and the micrometer screw. Since the instrument is to be immersed in a thermostat the water level of which is approximately at W, the joint between the cylinder *E* and the cap *D*, and that between *E* and the cover must be water-tight. Owing to the excellent machine work on the instruments[8] it has been found sufficient to cover both these joints with wide rubber bands. The piston rod is of invar to eliminate the error that otherwise would occur from its displacement in a non-homogeneous temperature field. Successful transmission of vibration from the quartz plate into the liquid depends upon good mechanical coupling between the quartz plate and the upper electrode, effected by placing a few drops of oil on the plate when the cup, *C*, is placed

[7] Six radial cuts are made from the outer edge of the circle toward the center, alternate segments are then bent in opposite directions.

[8] The instruments of this type have been constructed by Mr. Charles M. Childs in the instrument shop of the department of physics at the Johns Hopkins University.

in position. The interior of C and all parts of the cap, tube, piston and rod exposed to the liquid are heavily gold plated.

When the lead, L, of either type of instrument is connected to a source of oscillating potential, the quartz plate is forced into vibration and transmits compressional waves into the liquid. The waves can be reflected at a distance controlled by the micrometer screw, and successive positions may be found for which there is resonance. As the screw advances, shortening or lengthening the liquid column an indicating instrument in the electrical circuit passes through recurring cycles of readings from which the half wave length of the vibration in the liquid can be deduced with great precision.

CIRCUITS AND METHODS

Fig. 4 shows a Hartley oscillator with secondary coil, one terminal of the latter being grounded, the other connected to the lead L of the sonic interferometer. The Hartley circuit is tuned so as to give a

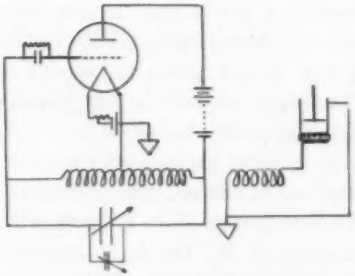

FIG. 4. *Simple form of oscillator for driving crystal of the interferometer.*

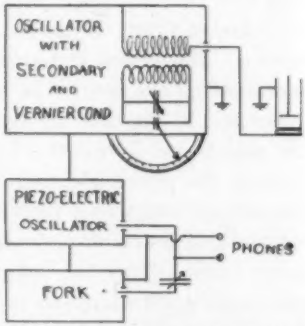

FIG. 5. *Ensemble for double heterodyne method.*

heterodyne beat note in the neighborhood of 1000 cycles per second with a precision piezo-electric oscillator of accurately known frequency (Fig. 5). One of the output terminals of an electrically maintained tuning fork giving a frequency of 1000 cycles per second is connected through a variable condenser to one of the phone terminals of the piezo-electric oscillator. A vernier condenser in the Hartley circuit serves to vary the heterodyne note by a small amount so that it can be kept in tune with the note of the tuning fork.

When the instrument is not moved the beat note remains constant to within 3 or 4 beats per second, i.e. the oscillator maintains its frequency

to within 3 or 4 parts in 500,000. The frequency of our standard piezo-electric oscillator was checked both against a standard American oscillator and also against a special standard which one of us brought back from Germany and which had been checked against the Standards of the Reichsanstalt. In both cases our oscillator at 20°C showed to within 4 or 5 cycles a frequency of 501,000 cycles per second.

If the micrometer screw of the sonic interferometer is turned, the vernier condenser readings, when unison is maintained between the fork and the heterodyne note, pass through a cycle of values indicating a sudden change as the liquid column passes through resonance. Near resonance the interferometer and Hartley systems act together with a common frequency which decreases rapidly through the resonance point as the liquid column is lengthened. The decrease is compensated

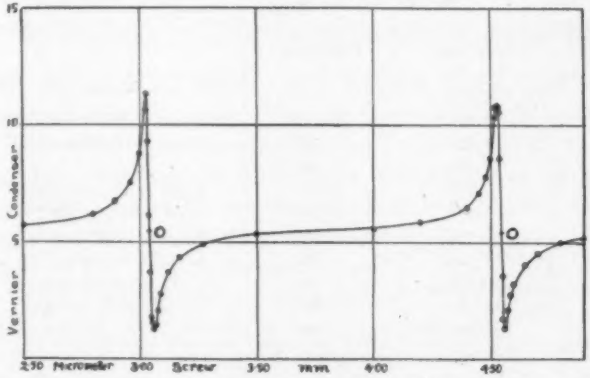

FIG. 6. *Vernier condenser readings (arbitrary scale) as a function of piston displacement, double heterodyne method, showing sudden dip through nodes at O.*

by a corresponding rapid decrease of capacity in the vernier condenser. Fig. 6 shows vernier condenser readings plotted against readings of the micrometer screw, the heterodyne note being always kept in tune with the note of the tuning fork. The figure is drawn from results with distilled water at 25°C. Some idea of the precision of determination of a single resonance point may be gained from the fact that repeated settings agree by this method to within two thousandths of a millimeter. With quartz plates of the diameter which we have used (50 mm), the nodes are equidistant throughout the entire range of the screw (25 mm). The pitch varies so rapidly through resonance, when the capacity is kept constant, that it is possible to leave the vernier

condenser in its mean position and read the settings of the screw for unison between the beat note and the fork in the region of rapid variation of pitch. In this way settings may rapidly be made by ear. They are indicated in the figure by the points O, O. In the practical application of this method we have adopted the following procedure.

Starting with a column of zero length, three successive nodal settings are found as described at the end of the last paragraph. Then the screw is advanced, usually about 15 mm, when three additional nodal settings are found in succession. From the data found is deduced the half wave length in the liquid and a statement of the precision of the observation. The following example illustrates this procedure, besides giving an entire series, Table 1.

TABLE 1.
25.35% Solution, NaCl $t = 22.05°$ C.

Setting	Screw, mm	Difference	
1	4.952		
2	6.992	2.040	Mean of first three, 6.993
3	9.036	2.044	Mean of last three 23.350
4	11.080	2.044	
5	13.126	2.046	Eight half waves, 16.357 mm.
6	15.176	2.050	$\lambda/2 = 2.0446 \pm .0004$ mm.
7	17.224	2.048	frequency = 437600 cycles/sec.
8	19.264	2.040	$u = 1789.4$ m/sec.
9	21.305	2.041	From the entire series
10	23.350	2.045	$u = 1789.3 \pm .3$ m/sec.
11	25.396	2.046	

The foregoing method, while of great precision, has the disadvantage that a very considerable amount of equipment is necessary and the observer must have the ability quickly to tune two notes accurately in unison. An equally precise method which requires far less in the way of equipment has recently been developed by us, and is the following:

A piezo-electric oscillator is coupled to the grid of a four-electrode, shielded-grid tube. (UX-222). The details of the circuit are shown in Fig. 7. Two or three stages of amplification carry the oscillations through the coil M. Coupled to M is the secondary N of a simple oscillating circuit consisting of the secondary and a variable condenser connected through a thermo-galvanometer. One side of the condenser is grounded, the other side being connected to a lead, L, of the sonic interferometer. The secondary is then tuned to resonance

with the primary oscillator, and coupling adjusted so that the thermo-galvanometer gives a suitable deflection. As the screw of the sonic interferometer is advanced, little effect is shown on the thermo-galvanometer readings until a resonance position of the screw is approached. A rapid dip now occurs in the thermo-galvanometer reading, due to the increased absorption of energy in the liquid at resonance. Fig. 8

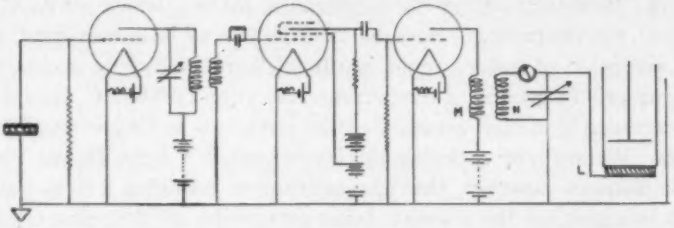

FIG. 7. *Constant frequency generator with tuned secondary and thermo-galvanometer.*

shows the galvanometer readings as a function of the screw readings as a resonance point is passed. The resonance position is easily determined to one or two thousandths mm. In order to determine whether there was any reaction upon the frequency of the primary oscillator, a second piezo-electric oscillator of nearly the same frequency was set up in the neighborhood. The beat tone of the two oscillators showed no perceptible variation due either to the tuning of the secondary circuit with which one of the oscillators was loaded, or to the passage of a resonance point in the interferometer.

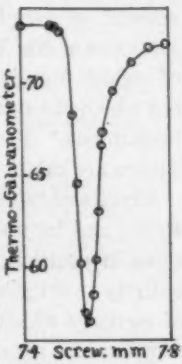

FIG. 8. *Galvanometer readings as a function of piston displacement, passing through a node.*

A word is necessary in order to justify the accuracy claimed for screw settings. In ordinary measurements with a micrometer screw, the screw is turned so that contact is made with a solid body. The rachet of the screw, or the practiced touch of the operator, ensures an accuracy of the order of 1/200 mm. In the present case, however, there is no contact to be made with a solid. The reading of the indicating instrument, vernier condenser, thermogalvanometer, etc., is a function of the position of the screw alone, variable back pressure being absent. Such slight back-lash as sometimes occurs in the mounting of the screw is always eliminated by approaching in

the same direction the successive settings of a series. Thus it has been possible, under usual working conditions to find resonance upon the same estimated tenth of a screw division, corresponding to 0.001 mm, and we have the record of a large number of observations in which the screw readings are consistent over the entire length of the screw (25 mm), to two or three thousandths of a mm. However, neither the temperature control, which we have employed, nor the purity of the substances, which we have measured, with the exception of water, would justify a claim of absolute accuracy of this order. In general, a temperature variation of 0.001 C. should not be exceeded if the full accuracy of the method is to be preserved in all cases. We are now enclosing the instrument in a large Dewar Flask. It is obvious, however, that the instrument furnishes a new tool of high precision for the chemist, being comparable to the refractometer or the pycnometer for empirical analysis and the verification of purity.

It should further be remarked that it is necessary to keep the power supplied to the plate of the interferometer within low limits in order to avoid heating within the instrument.

RESULTS

The sonic interferometer has been used for the determination of the velocity of sound at various temperatures in distilled water, mercury, solutions of NaCl, KCl, and NaI. A survey has been made of a number of organic liquids and of a mixture of glycerine and water, for the bearing which the resulting information might have upon the design of the instrument.[9] These results have been published elsewhere,[10] but a few curves are exhibited here by way of illustration.

Results obtained for the velocity of sound in water between 0° and 40°C., and for mercury between 0° and 70° are shown in Fig. 9. Variations in position of points from a smooth curve are to be attributed entirely to insufficient temperature control. This was particularly true of mercury which was studied in an improvised cell poorly adapted to temperature regulation.

The results for NaCl solutions are shown in Fig. 10. For a comparison of the results obtained by the present method with those of previous

[9] In the work with mercury the liquid was contained in a pyrex beaker, the bottom of which was ground plane inside and out, set upon the top electrode of the quartz plate. The piston in this case was made of the bottom of a small pyrex beaker ground plane after being fused to a pyrex tube to serve as piston rod.

[10] Phil. Mag , loc. cit.

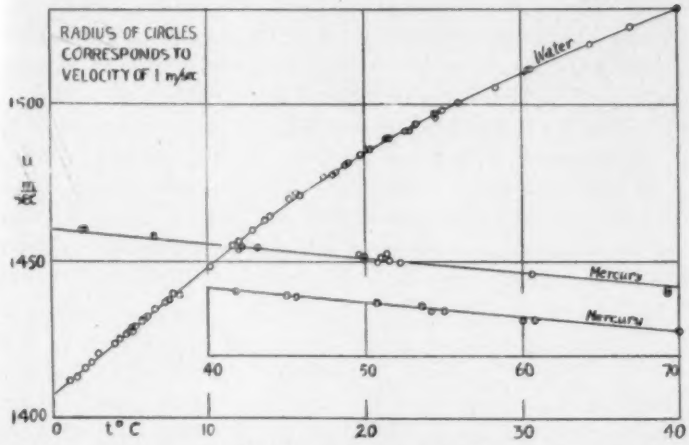

FIG. 9. *Velocity of sound in water and in mercury as a function of temperature.*

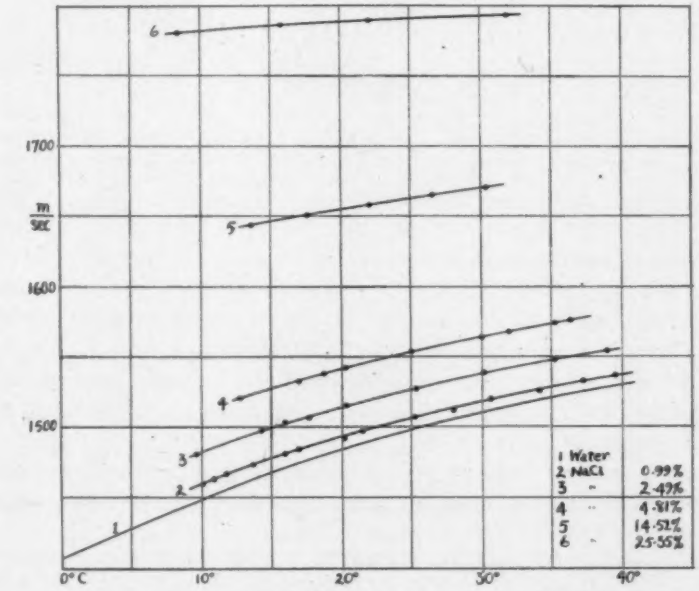

FIG. 10. *Velocity of sound in solutions of NaCl as a function of temperature.*

observers of the velocity of sound in liquids, the values of the velocity of sound in NaCl solutions as a function of the per cent of salt in solution have been calculated from our results for a temperature of 16°C, and are shown in Fig. 11. The resulting curve is the nearly straight line A. The other curves in the figure are reproduced from a summary of data by other observers, at the same temperature.[11] Curve *B* is computed from the measurements of Tait. Curve *D* shows three points obtained by Dörsing for the velocity of sound, and curve *V*, those by Veenekamp; the last two observers using audible frequenices and correction factors for the effects upon the wave length of the boundary walls.

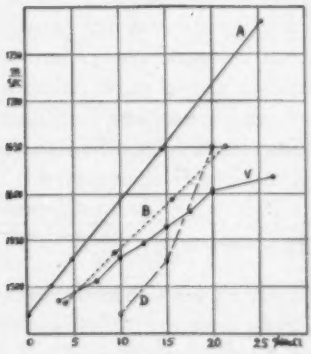

FIG. 11. *Curve A; velocity of sound at 16°C in solutions of NaCl as a function of per cent by weight of salt. Curves B, D, and V; calculated and measured values of other observers, reproduced from Handbuch der Physik, 8, p. 642.*

The results of Dörsing and Veenekamp are typical of available data on the velocity of sound in liquids. Most of the discrepancies hitherto existing seem to be due to different degrees of approximation in the application of correction formulas.

In the use of the instrument described here no such corrections are required. Exhaustive experiments have shown that the dimensions and material of the cell containing the liquid are without effect upon the measured velocity. The precision attainable under conditions of good temperature control indicates that the instrument will be available as a powerful aid to analysis. We have shown elsewhere that from its results thermodynamic coefficients for liquids can be calculated with a high degree of precision.

[11] Handbuch der Physik, *8*, p. 642.

It may be pointed out that the sonic interferometer when used with a tuned secondary circuit as in Fig. 7 may be used as a secondary standard of precision for the rapid determination of the frequency of crystal oscillators or for the calibration of wave-meters.

Mr. E. B. Freyer, of the department of chemistry of The Johns Hopkins University is using an instrument of the type shown in Fig. 3 in a study of the thermodynamic properties of various salt solutions and organic liquids.

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A VISUAL METHOD FOR STUDYING MODES OF VIBRATION OF QUARTZ PLATES

By A. M. Skellett

ABSTRACT

A large number of beautiful patterns formed on the surface of a piezo-electric quartz plate by the glow discharge at low pressures of gas were observed at various radio frequencies of the exciting oscillator. They are caused by different modes of vibration of the plate of which there seems to be a great number. Evidence in support of the theory that the bright spots in the pattern occur at the antinodes of standing waves in the plate is presented from which it appears that the value of Young's modulus is the same for directions at angles of from 0 to 78 degrees from the optic axis. These patterns explain the multitude of frequencies at which a piezo-electric quartz plate will vibrate observed by Cady and others.

Water vapor was found to condense on the crystal in the configuration of the pattern corresponding to the last mode of vibration of the crystal and a thin spark was produced about 13 mm long between the electrodes and over the surface of the vibrating crystal at a pressure of 5 mm.

INTRODUCTION

When quartz plates are cut for use as piezo-electric oscillators in either of the two methods commonly used, i.e., parallel to a natural face of the crystal, as in Fig. 1, or perpendicular to a face, besides the three fundamental frequencies expected,[1] a multitude of other frequencies at which the crystal will vibrate may be detected by means of a telephone in the plate circuit of the exciting oscillator. As the frequency of the oscillator is varied, at a characteristic frequency of the crystal, the crystal absorbs energy from the oscillator and starts to vibrate and as the oscillator frequency continues to change, a beat note between the dying out oscillations of the crystal and the oscillations of the exciter is heard as a "chirp" in the receiver. In some cases these characteristic vibrations are so close in frequency that a continuous beat note may be heard. These "troublesome, non-descript vibrations" led Cady[2] to abandom plates as resonators and use rods instead. Through the range of frequencies covered in this experiment, there was a pattern or an indication of a pattern at practically all of the frequencies at which a "chirp" was heard. The number of these "chirps" was very large. A complete frequency spectrum could not be worked out for the crystal because of the limitations of the apparatus, however, as many as forty-two of these "chirps" were counted in one interval of 90 kilocycles.

[1] A. Hund, Proc. I. R. E., *14*, p. 452; August 1926.
[2] W. G. Cady, J.O.S.A. & R.S.I., *10* p. 480; 1925.

The production of a difference of electric potential between the two surfaces of a quartz plate when it is mechanically deformed is called the direct piezo-electric effect while the opposite of this or the deformation of the crystal due to an applied electric field is called the converse effect. Now if we mount a small crystal in a partially evacuated chamber between two flat electrodes covering top and bottom surfaces but not touching them and apply across the electrodes an alternating emf just below the potential necessary to ionize the gas and of a frequency corresponding to its fundamental vibration, the crystal will vibrate mechanically as a whole in consequence of the converse effect. For condensation all regions will become thinner and for a rarefaction all regions will become thicker. However, the vibration of the crystal, since we are at resonance with its fundamental frequency, will build up in amplitude until the difference of potential in consequence of the direct effect is greater than the applied emf and the gas may become ionized. This ionization has been made use of to show the fundamental and harmonics of vibrations of quartz rods.[3] Standing waves were set up in the rods, the glow appearing at the antinodes.

APPARATUS AND PROCEDURE

The plate was cut as shown in Fig. 1 with the optic axis parallel to its length and one of the three piezo-electric axes, A, parallel to its width. It should be stated here that although it was known that the plate was cut with the faces parallel to an electric axis, it was not

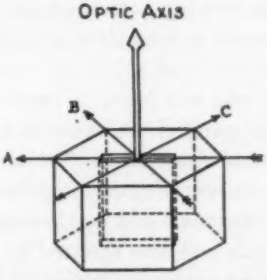

FIG. 1. *Orientation in quartz.*

known which dimension, length or width, was parallel to this axis. This was found from an analysis of the glow patterns described later in the article.

[3] E. Giebe—A. Scheibe, ZS. f. Physik. 13, pp. 335–344; 1924.

The dimensions of the crystal were found to be as follows: length =27.1 mm, width 20.8 mm and thickness 2.44 mm. The fundamental frequency due to the thickness was 382 meters or 785 kilocycles. It was mounted as shown in Fig. 2 and Fig. 24. The lower electrode was in the shape of a shallow box about one mm deep, allowing about .5 mm clearance all around the crystal so that it was perfectly free. The top electrode was about 1.5 mm from the surface of the crystal and the ionized gas around it probably also acted somewhat like an electrode. The bright glow immediately around the wire served to locate it on the photographs. A pattern similar to the one on top might be expected[4] on the bottom if two point electrodes were used, one above and one below the center of the plate but since the bottom pattern would be out of focus and would fog the photographs, the arrangement shown was used.

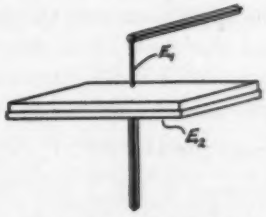

FIG. 2. *Mounting of crystal.*

For some patterns only a small portion of the lower side of the plate would glow, its position varying with the pattern.

The auxiliary equipment consisted of a standard Hartley oscillator using 190 volts on the plate and a UX 171 tube. For more power a UX 210 tube with 250 volts was used. A small three plate vernier concenser was connected in parallel with the main condenser and a glass rod a foot long on the shaft gave fine adjustment and eliminated body and hand capacity. The alternating emf impressed across the electrodes was obtained from the terminals of a coil loosely coupled to that of the oscillator. In general this coil was shunted by a condenser so that it could be tuned to the resonant frequency of the particular mode of vibration although the coil alone was sufficient for many of the patterns. A wavemeter located about eight inches from the oscillator coil completed the apparatus. The values of frequency given are not to be taken as exact since the wavemeter was not of a very accurate type.

[4] F. Giebe—A. Scheibe, Elektrotech Zeit., *47*, pp. 380–385; 1926.

The crystal was mounted in the center of a pyrex bulb of about 10 cm diameter with a flat window at the top directly over the top electrode. Argon at about 5 mm was used. At lower pressures the patterns were less distinct and at higher pressures, although the definition is better and the pattern lies closer to the surface of the crystal, the spots which are 180 degrees out of phase have a greater tendency to be connected together by the glow. This makes it harder to locate the centers of the antinodal regions which are important for interpreting the patterns. Moreover more power than was available is required for most of the patterns at higher pressures.

ANALYSIS OF PATTERNS

As the frequency of the oscillator is varied, the "glow patterns" appear and disappear with lightning rapidity on the surface of the crystal, some of them separated by only 400 or 500 cycles. Where they are close together, as the frequency is varied, the pattern fades somewhat in intensity, the spots or lines shifting to their new positions, and the new pattern "fades in" and increases to its full brilliancy. This process is entirely reversible. Such a change is shown in Figs. 12 to 16. Fig. 14 is a transition between Figs. 13 and 15. Other changes are perfectly abrupt and the pattern goes directly from one kind to the other. It seems that the patterns are made up of standing compressional waves in various combinations and possibly Chladni or other types of plate vibrations.

In order to check this theory we make use of the relationship between the wave length of the standing waves and the frequency.

$$f = v/\lambda$$

Since Young's modulus is different for directions parallel to and perpendicular to the optic axis of the crystal, we have two velocities for waves in these two directions from the relation

$$v = (Y/\rho)^{1/2}$$

The value for Y parallel to the axis is 10.3×10^{11} and perpendicular to it is 7.85×10^{11}. The density of Quartz is 2.654. Thus

$$v_1 = 6.24 \times 10^5 \text{ (parallel to axis)}$$
$$v_2 = 5.38 \times 10^5 \text{ (perpendicular to axis)}$$

from which

$$f = 6240/\lambda \qquad (1)$$

and

$$f = 5380/\lambda \qquad (2)$$

where λ is in mm and f is in kilocycles.

According to the theory outlined in the introduction we would expect the glow to take place at the antinodal regions and if we measure from the center of one glow to the center of the next, we will have one half of the wave length of the wave in the crystal. Multiplying by 2 and inserting in the proper one of the two equations above, we can find the frequency at which a standing wave of this dimension might appear to check with the frequency measured by the wavemeter when the pattern was photographed.

A selection of the most complete in detail of the many patterns photographed, is reproduced in the accompaning figures. Where the outline of the crystal was indistinct it was drawn in on the negative. A large number of the patterns are hazy and similar to Figs. 17 and 18. Some are unstable and do not persist long enough to photograph but break into a more stable form. One of these is what appears to be a series of standing waves that break into Fig. 18 without noticable change in frequency.

Fig. 3 has the appearance of a set of standing waves from the center to the edge. If parallel lines are drawn through the centers of the glowing ridges in the photograph and the distance between them measured and reduced to the size on the crystal, we get 6.6 mm for half a wave length. This corresponds to a frequency of 850 kilocycles from Eq. (1) for waves parallel to the optic axis. The wavemeter read 355 meters or 844 kilocycles. The difference of 6 kc is well within the range of experimental error.

Fig. 4 shows a very stable pattern. The two lines were drawn through what appeared to be the centers of the glowing ridges by means of the spots at the ends of the rows. Measurement of the distance between the antinodes along the lines shown gave 7.11 mm for the wave length in the crystal which corresponds to 845 kc from Eq. (1). The value measured was 840 kc. Now using the distance across the two lines, i.e. between axes of the sets of standing waves, we get from Eq. (2) 421 kc or half of 842. This seems to indicate that the crystal is vibrating crosswise at half of the frequency. These measurements were checked on several photographs of this pattern, one of which showed more detail but was too faint for good reproduction. The spot at the center of the bottom and the one nearest the top lie very nearly in the center of the

next antinodal region on either side. The glow ridges do not line up because the axes are not perpendicular to the ends of the crystal from which the waves are reflected and there is a node for each set at the crystal end. Cady has shown[2] that the ends of rods need not be square for good reflection of waves.

FIG. 3. $f=844kc$ FIG. 4. $f=840$ FIG. 5. $f=830$

Fig. 5. It is not so easy to lay off axes for the standing waves in this pattern. However measurement between antinodal regions near the top and bottom of the photograph give an average of 6.6 mm for λ or 851 kc. This is not in very good agreement with the measured frequency of 830 kc. The sets of standing waves seem to be in phase or 180 degrees out of phase indicating that the axes of the waves are either nearly parallel to the edges of the crystal or at a much greater angle than in Fig. 4.

Fig. 6. The wave length measured at several places on the crystal averages 8.003 mm which gives 779 kc as against 770 kc measured by the wavemeter.

Fig. 7. Here we seem to have standing waves from the middle of the crystal to the edge at the top of the photograph. The two ends act as rods with the center region of the crystal possibly inactive. The distance between spots on the crystal is 14.2 mm which gives from Eq. (2) a frequency of 382 kc. Twice this is 764 which is in good agreement with 765 kc measured by the wavemeter.

Figs. 8, 9, 10, and 11. This group is a series in the order of their appearance as the frequency is decreased. First the glow at A appears alone then C and finally B. Further decrease in frequency produces Figs. 9, 10, and finally 11, after which the whole pattern disappears instantaneously. From A to B or A to C on the crystal measures 22.5 mm and Fig. 10 indicates that there are three nodes along these lines so that we must divide by three to get half the wave length. Using Eq. (1) although the line AB is 78 degrees from the optic axis, the corresponding frequency is 828 kc which is the same as that measured. If there are

three half waves between A and B as Fig. 10 indicates we would expect B and C both to be 180 degrees out of phase with respect to A and therefore A should appear first with respect to B or C or vice-versa according as it agrees in phase with the nearest electrode or not. It has

FIG. 6. $f=770$

FIG. 7. $f=765$

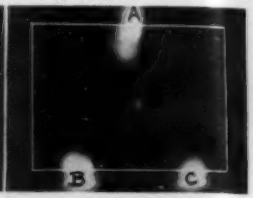

FIG. 8. $f=832$

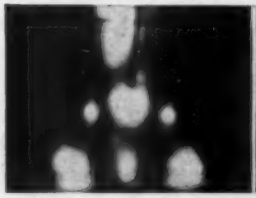

FIG. 9. $f=830$

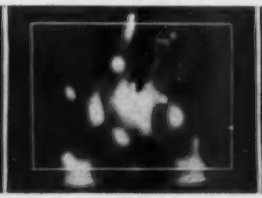

FIG. 10. $f=828$

FIG. 11. $f=821$

sometimes been possible to make B and C appear before A. B and C do not appear together because more energy is needed for three than two and as we approach resonance the energy absorbed by the crystal increases. Another fact that points to these conclusions concerning the manner of vibration is that the terminal points of the standing waves at the sides of the crystal glow just as would be expected if they were antinodes. The smaller spots on Fig. 9 are slightly displaced toward the top electrode but as the pattern comes in more detail and the glow settles closer to the crystal they move out to their proper positions. Fig. 11 is probably made up of several other systems of vibration besides this triangular one and since the right and left side of the pattern are not symmetrical it is hard to tie up all of the spots to definite configurations.

Fig. 12. This appears to be made up of two sets of longitudinal standing waves crossing each other at an angle of about 124 degrees. Twice the distance between antinode rows is 7.49 mm corresponding to a frequency of 833 kc using Eq. (1). This compares well with the measured frequency of 830 kc.

Fig. 13 is Fig. 12 in less detail. Fig. 14 is a transition stage between Figs. 13 and 15. Very slight changes in frequency such as are caused by bringing the hand within several inches of the oscillator shift the lines from one pattern to the other. Another small decrease in frequency

FIG. 12. $f=830$ FIG. 13. $f=818$ FIG. 14. $f=826$

gives Fig. 16. The mean distance between the spots in the rows at the edges of the crystal is 4.18 mm. From Eq. (2) this is found to correspond to a frequency of 644 kc which does not seem to be in any simple ratio with the 820 kc measured by the wavemeter.

FIG. 15. $f=824$ FIG. 16. $f=820$ FIG. 17. $f=625$

FIG. 18. $f=1300$ FIG. 19. $f=840$ FIG. 20. $f=838$

Figs. 17, 18, 19, 20, and 21 are reproduced as representative of the various types of patterns. Fig. 20 resembles a Chladni figure vibrating in four segments. Adjacent segments would be 180 degrees out of phase with each other and for a limited amount of energy only two would appear.

Fig. 22 measures 6.66 mm for the wave length of the wave in the crystal assuming that there are standing waves parallel to the optic axis. This gives a frequency of 936 kc which is not in agreement with the measured frequency of 792 kc. Therefore it is probably part of some larger pattern.

FIG. 21. $f=743$ FIG. 22. $f=792$ FIG. 23. $f=803$

Fig. 22 also looks like a set of antinodal regions of standing waves but since measurements show that there would be neither a node nor an antinode at the edge of the crystal for reflection, it too is part of a larger pattern.

Higher pressures of the gas give more clear cut patterns as mentioned previously and it is expected that many of the patterns which were only partially visible will be brought out in more detail under higher pressures and more power.

OTHER EFFECTS

Fig. 25 was taken at 16 mm pressure. It has the appearance of an arc discharge between two isolated spots on the crystal not symmetrical with respect to the electrode and probably 180 degrees out of phase. Where isolated spots appear even at 5 mm pressure there was almost

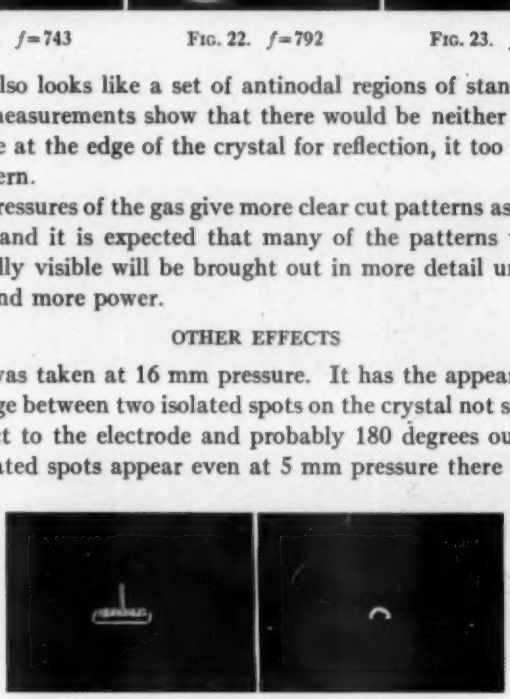

FIG. 24. FIG. 25.

always a fan or brush shaped discharge over each one. It was roughly estimated that the average velocity of the surface of the crystal was of the order of 100 cm per second so that these ionized molecules are

probably projected upward from the crystal at the spots. The writer has succeeded in producing a bright well defined column of these ionized molecules about 3.5 mm high and 1.5 mm in diameter over a small crystal using a ring shaped electrode. The column appeared in the center of the ring and extended above it.

Another effect observed was that water vapor, left in the bulb walls by the breath while altering the glass apparatus, settled on the crystal in approximately the same pattern as was last visible. This phenomenon may be explained by charges left on the crystal by the last mode of vibration since quartz is such a good insulator. The water and other dirt which had accumulated on the plate promptly disappeared when it was set into vibration, leaving the surface perfectly clean.

It was also noticed that when the voltage was cut down to the threshold value for ionizing the gas by crystal vibration, a thin momentary spark would sometimes jump between the electrodes close to the surface of the crystal. It did not take the shortest route but varied in length up to about 13 mm. There was always a haze in the region at the same time, caused no doubt by part of a pattern, and the spark took place only at the frequency of some pattern. The pressure was 5 mm.

CONCLUSIONS

The multitude of frequencies at which a piezo-electric quartz plate will vibrate correspond to as many different modes of vibration of the plate. The theory that these modes of vibration are due to standing waves is partially verified and the value of Young's modulus for quartz crystals for directions at angles of from 0 to 78 degrees from the optic axis appears to be the same as the value parallel to the axis. Sections in any direction in the crystals may have longitudinal standing waves set up in them, the lengths being such that there is either a node or an antinode at each end.

This report is presented in the nature of a preliminary to a more exhaustive investigation of the phenomena using round and rectangular sections of both this and the "Curie" cut, other electrode arrangements, and better auxiliary equipment.

UNIVERSITY OF FLORIDA,
GAINESVILLE, FLORIDA.
APRIL, 1928.

PERIOD OF A LOADED CONICAL JOLLY BALANCE SPRING

By R. B. Abbott

ABSTRACT

An expression for the period of a conical Jolly balance spring is deduced theoretically and the result is verified by experimental data. By some assumptions which simplify the equation of motion it is reduced to that for simple harmonic motion from which the period is obtained. The period is:

$$T=2\pi\sqrt{\left(M+\frac{m_0}{3k}\right)\frac{k}{mg}}$$

M, is the mass of the load, m_0 is the mass of the spring, k is the extension of the spring for a load m and $C=(r_2/r_1-1)$

$$K=\frac{5[(c+1)^2+1]^2(c+2)^2}{(160+480c+696c^2+620c^3+360c^4+135c^5+30c^6+3c^7)}$$

r_2 is the radius of the large end coil, r_1 is the radius of the small end coil. Very approximately, $K=1+C/3$ so that

$$\frac{m_0}{3k}=\frac{m_0}{2+r_2/r_1}$$

INTRODUCTION

Two kinds of springs are now being used on Jolly's balance, namely, the straight helical spring and the conical spring. Probably the first complete statement of the thory of helical springs was given by Kelvin and Tait.[1] The present paper deals with the theory of the period of a loaded conical spring. The whole treatment is an approximation based on the assumption that the applied load is large compared with the weight of the spring. It is very similar to the approximation given for helical springs in G. F. C. Searle's book on "Experimental Harmonic Motion,"[3] which, in turn, was suggested in Lord Rayleigh's "Theory of Sound."[4] The theory of its extension under an axial force can be found in "Applied Elasticity" by Timoshenko and Lessells.[2]

EXTENSION OF A LOADED CONICAL SPRING

Let r be the variable radius of the coils of the spring and r_1 and r_2 the radii of the small and large end coils respectively. If r makes an

[1] Kelvin and Tait. "Natural Philosophy," *2*, arts, pp. 604–607.
[2] Timoshenko and Lessells. "Applied Elasticity," p. 32.
[3] G. F. C. Searle's "Experimental Harmonic Motion," Art. 30.
[4] Lord Rayleigh's "Theory of Sound," *1*, Art. 88. Second edition.

angle θ with r_1 $r = r_1 + (r_2 - r_1/2\pi n)\,\theta$ where n is the total number of coils on the spring. For our purpose it will be assumed that the extension is all due to torsion and that the pitch angle and changes in the pitch angle are zero.

The twisting moment at any point along the wire is $M_1 = Pr$ where P is the applied axial force. From Hooke's law this moment is equal to $M_1 = \frac{1}{2}\pi G\,\rho^4\,d\beta/dL$ where G is the coefficient of torsional rigidity, ρ is the radius of the wire, β is the angle of twist and L is the length of the wire.

The work done in twisting the wire through the angle β is $W = \int_0^\beta M_1 d\beta$. If X is the extension of the spring for an axial load P, when Hooke's Law is followed the work done is $W = \frac{1}{2}XP = \int_0^\beta M_1 d\beta$. This operation results in the following expression for the extension:

$$X = \frac{nP}{G\rho^4}\,(r_1^2 + r_2^2)(r_1 + r_2)$$

PERIOD OF A LOADED CONICAL SPRING

The method used to find the period of oscillation is outlined as follows: Set up an expression for the total energy of the system, differentiate it with respect to time and get an equation of motion for the system. By certain assumptions this motion is considered as simple harmonic motion and its period evaluated. In taking into consideration the inertia of the spring as well as the load, the method becomes very complicated but not really difficult.

If the velocity of the load is U and that of any part of the spring is V, it can be seen from the expression for the extension of the spring that these velocities are related (assumed conditions granted) as follows:

$$\frac{U}{2\pi n(r_1^2 + r_2^2)(r_1 + r_2)} = \frac{V}{\theta(r^2 + r_1^2)(r + r_1)}$$

The velocity V for any element of mass $dm\,(=\sigma r d\theta)$ when substituted in the kinetic energy integral gives the kinetic energy of the spring as follows:

$$E_0 = \int_0^{2\pi n} \tfrac{1}{2}(\sigma r d\theta)V^2$$

σ is the mass of the wire per unit length. The total mass of the spring is $M_0 = \int_0^{2\pi n} \sigma r d\theta$. These integrals give:

$$E=\frac{1}{2}\frac{m_0}{3K}U^2$$

$$K=\frac{5[(c+1)^2+1]^2(c+2)^3}{(160+480c+696c^2+620c^3+360c^4+135c^5+30c^6+3c^7)}$$

$$C=\left(\frac{r_2}{r_1}-1\right)$$

The total kinetic energy of the spring with load M is:

$$E=\frac{1}{2}\left(M+\frac{m_0}{3K}\right)U^2$$

The potential energy of the system for an extension X is by Hooke's Law:

$$W=\frac{1}{2}\left(\frac{mg}{h}\right)X^2$$

h is the extension of the spring by a force of mg where g is the acceleration of gravity.

Assume that the system is conservative so that the total energy is constant so that $E+W=$constant.

$$\frac{dE}{dt}+\frac{dW}{dt}=0$$

By using the expressions for E and W in the above indicated operations one gets

$$\left(M+\frac{m_0}{3K}\right)\frac{d^2x}{dt^2}+\left(\frac{mg}{h}\right)X=0$$

$$\frac{d^2x}{dt^2}=-\left[\frac{\left(\frac{mg}{h}\right)}{\left(M+\frac{m_0}{K3}\right)}\right]X$$

This is the required equation of motion which turns out to be simple harmonic motion with a period

$$T=\frac{2\pi}{\left[\frac{mg/h}{(M+m_0/3K)}\right]^{1/2}}=2\pi\sqrt{\left(M+\frac{m_0}{3K}\right)\frac{h}{mg}}$$

This expression holds for any conical spring. It reduces to the case of a straight helical spring when $r_1=r_2$. In that case

$$C=0,\quad K=1 \text{ and } T=2\pi\sqrt{\left(M+\frac{m_0}{3}\right)\frac{h}{mg}}$$

The expression for K can be simplified by making a simple approximation as follows:

If K is plotted as ordinate and C as abscissa one gets almost a straight line. By inspection of this line, one can write $K=1+c/3$ very approximately, since

$$C=\frac{r_2}{r_1}-1,\qquad K=\frac{2r_1+r_2}{3r_1}$$

so that

$$\frac{m_0}{3K}=\frac{m_0}{2+r_2/r_1}$$

EXPERIMENT WITH A LOADED CONICAL JOLLY BALANCE SPRING

The data in the following tabulation were taken with an error less than one half of one per cent. The agreement with theory is within the limits of experimental error.

$m_0=13.825$. Top radius $r_1=0.6195$ cm. Bottom radius $r_2=1.184$. Radius of wire $=.02825$ cm. $C=0.915$. $K=1.33$. $N=126$ turns. $G=7.47\times10^{11}$ dynes/sq. cm. The extensions were taken for an increment of load equal to 20 grams.

TABLE 1.

Load (grams)	Extension (cm/gm)	Period (observed)	Period (calculated)
20.07	.7925	0.866 sec.	0.866 sec.
30.07	.7925	1.036	1.034
40.07	.7910	1.178	1.178
50.07	.7882	1.302	1.303
60.07	.7855	1.420	1.417
70.07	.7825	1.522	1.521
80.07	.7795	1.618	1.618
90.07	.7765	1.708	1.709
100.07	.7730	1.792	1.794
110.07	.7690	1.874	1.874

While taking the periods, the weights (which constituted the loads on the spring) were attached by means of a flexible small thread,

weighing .07 gms, so that the spring could rotate freely without impressing a turning moment on the weight. The weight of the thread was added to the load as shown in the tabulated data and results.

The effect on the period, of attaching the weight rigidly to the spring, was investigated and found to be as follows:[5]

TABLE 2.

Load	Period	
	Vertical	Rotational
50 gms.	1.304 sec.	0.90 sec.
100 gms.	1.808	1.54

This shows that the vertical period is increased by attaching the load rigidly to the spring.

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[5] A. Sommerfeld, coupled "Oscillations of a Helical Spring," J.O.S.A. & R.S.I., *7*, p. 529 1923.

ON THE MEASUREMENT AT RADIO FREQUENCY OF THE CONDUCTIVITY OF LIQUIDS WITHOUT IMMERSED ELECTRODES

By W. F. Powers and M. F. Dull

The recent appearance of the paper by Burton and Pitt[1] entitled "A New Method of Conductivity Measurement by means of an Oscillating Valve Circuit," has suggested to us the desirability of reporting our method of testing the effects caused by small volumes of liquids (or solids) when introduced within a small solenoid forming part of a triode circuit that is not a generator of oscillations (Fig. 1).

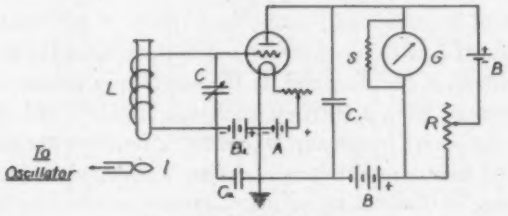

Fig. 1. *Wiring diagram.*

One of the present authors[2] noticed the effect of a liquid or solid core within one of the inductances of two closely coupled circuits in 1920 while working on dielectric constants of liquids. This work was not resumed until 1926 when the circuit described by Dowling and Preston[3] was modified somewhat. With this scheme we encountered the phenomenon of cessation of oscillations which is the basis of the method of Burton and Pitt.

It then occurred to us that the theoretical treatment of the problem might be simpler if a non-generating circuit could be used, and the first of the two circuits published by Gunn[4] "On the Measurement of very small Changes of Capacity" suggested itself as being equally applicable to the measurement of very small changes in inductance. We found this to be the case and have used it with very minor changes (Fig. 1).

[1] Phil. Mag., pp. 939–943; May, 1928.
[2] Phys. Rev., n. s., *15*, pp. 535–536; June, 1920.
[3] Phil. Mag., pp. 537–545; March, 1922.
[4] Phil. Mag., pp. 224–226; July, 1924.

In this report we wish primarily to draw attention to the fact that this method is sensitive to the introduction of a volume of liquid less than 20 cc within coil *L*. At this time we do not emphasize results, only giving a few numerical data indicating what the circuit has done. We are not prepared to say just how the dielectric constant and conductivity of the inserted medium enter the results and theory.

In Fig. 1, *L* is a single layer coil of 42 turns, diam. 5.5 cm, length of winding 9.0 cm on the central portion of a vertical glass tube fitted with stopcocks top and bottom for use of larger volumes of liquid. *C* is a precision variable condenser set at about 500 micro-micro-farads; C_1, C_2 are fixed condensers of 1 and 0.05 microfarads respectively; *G* is a reflecting galvanometer of 12 ohms shunted by *S* of 50 ohms; *R* is a variable resistance box. A 199 type tube is used with *B* 90 volts, B_2 9 volts and B_1 a single dry cell.

By means of a pulley and string test-tubes of different sizes were lowered inside of *L* without the observer approaching the circuit which was not shielded. A coupling coil, 1, of a single turn placed 10 cm below *L* supplied energy from a Hartley oscillator having a 201-*A* tube with 45 volts on the plate; frequency about 600 kilocycles per sec.

The method has generally been to adjust *C* to a value near resonance where a change in *C* of 0.6 micro-micro-farad produced a change in the galvanometer deflection of about 40 cm (scale 50 cm long). Due to lack of shielding and the possibility of thermo-currents there is yet something to be desired in the elimination of creeping of the galvanometer. With such adjustment the introduction of 80 cc of distilled water throws the galvanometer off scale, consequently so far, we have adjusted *R* to give a convenient galvanometer reading when a certain test-tube of distilled water was placed within *L*, and have then noted the changes in reading of the galvanometer when similar test-tubes filled with the same volume of various liquids were introduced. In general it has been necessary to short the galvanometer while changing the medium inside *L*.

To give an idea of the sensitivity of the apparatus, empty test-tubes *A* and *B* were lowered within *L*. Dimensions of *A*, length 15 cm, outside diam. 1. 5 cm; for *B* length 15 cm, outside diam. 2.3 cm. The change in galvanometer deflection on introducing *A* was about 1 cm and 3.0 cm for *B*; larger tubes gave larger deflections. These results suggest that the dielectric constant of the medium inserted within *L* may play a part. The change in deflection on replacing tube *B* containing 80 cc of distilled water by a similar tube containing the same amount of 0.025% solution by weight of NaCl in distilled water was about 26 cm. Chang-

ing from this salt solution to one of strength 0.038% produced a change in deflection of about 8 cm. On another day when the sensitivity was comparable, but not identical, the changes in deflection on inserting tubes of size *A* containing 20 cc of benzene, alcohol, and distilled water, respectively, were 1 cm, 10 cm, and 19 cm (corrected for tube).

It is of interest to note how the deflection of the galvanometer varies, under the above conditions of use, as a tube containing the medium is lowered within *L*. Fig. 2 was obtained by lowering a tube of size *A*

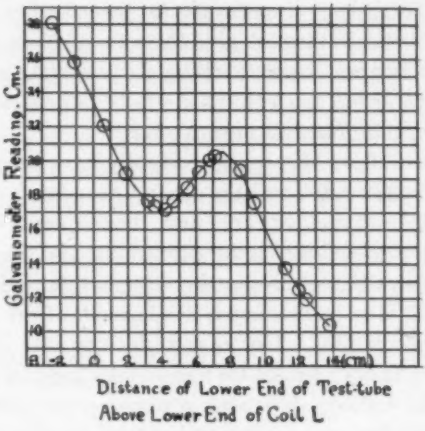

FIG. 2

containing 20 cc of distilled water to different positions; when the bottom of the tube is only a couple cm within *L* the galvanometer deflection is about half of that obtaining when the bottom of tube A is about 2 cm below the bottom turn of coil *L*.

We have not yet examined whether *L* has the best dimensions for this work. It is felt that the circuit may be made considerably more sensitive by using a 222 type tube and a stage of amplification if necessary, before the galvanometer branch, and more stable by shielding. It is hoped to continue this work after improving the set-up along the lines suggested.

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THE VIBRATION GALVANOMETER OBSERVED STROBOSCOPICALLY

By J. B. Saunders

When the vibration galvanometer is being used in the null method for measuring electrical quantities, its indications of unbalance in the net-work does not permit the operator to tell whether the settings are too high or too low. Both cases give the same phenomenon, namely, a hazy broadened image. A simple method of knowing whether the settings are too high or too low would seem to be of general interest and it is on this assumption that this note is offered.

Two methods of doing this stroboscopically have been tried with success, one using a sector disc and the other a neon lamp. The conditions to be met with in both methods are: first, the frequency of illuminations must equal that of the galvanometer vibrations; and second, their phase difference must be adjusted to that for which illumination occurs when the galvanometer is at its maximum displacement from equilibrium.

The Sector Disc Method. Let us consider the case of a simple net-work, such as De Sauty's bridge for measuring capacitance, and let only one resistance be varied. By using a strong point-source of light its image may be thrown on a screen and viewed by looking through the slits of a stroboscopic disc. The conditions for resonance between the galvanometer vibrations and the disc can be satisfied by using a synchronous motor to run the disc and a common source of current to energize both the bridge and the motor. The second condition is satisfied by either moving the eye about the disc or moving the disc perpendicular to the beam. When these two conditions are thus satisfied, the point will appear on one side or the other of the equilibrium point when the bridge is out of balance, and at the equilibrium point when the bridge is balanced. An increase in the variable resistance will move the point in one direction only and a decrease will move it in the opposite direction. Thus the position of the point tells the operator whether the settings are too high or too low and proper adjustments may be made.

The Neon Tube Method. If a "carona" type of neon tube is used for the source of light, it can be substituted in the circuit instead of the motor, and we have the first condition to be met satisfied. The tube will glow

with double the frequency of the galvanometer vibrations, each electrode glowing alternately. Since this gives two images the tube must be mounted so that either terminal may be singled out for observation. This can be done by having the terminals in a plane perpendicular to the plane of vibration of the galvanometer. The second condition to be met is satisfied by placing the right kind and amount of impedance in the circuit of the neon lamp or in the bridge circuit between the bridge and source. In this case an increase in the variable resistance will always move one image to the right and the other to the left. When balance is being approached the images approach their respective equilibrium points. If the resistance is changed too much for balance the images exchange sides.

The frequency tried in these experiments was limited to sixty cycles. There is no apparent reason why the method could not be employed with any frequency for which vibration galvanometers are generally used.

In conclusion the author wishes to express his appreciation to Dr. L. G. Hoxton for suggestions and encouragement in devising these methods.

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Collected Researches of the National Physical Laboratory. Vol. 20, 1927. v+444 pages. H. M. Stationery Office, London. 18s. 6d. Net.

The prospective purchaser of this volume will perhaps be best served if we give a detailed list of its valuable contents. All of the papers are reprints of previous communications by members of the laboratory, and all of them deal with optics. The volume begins with reprints of papers by Mr. T. Smith, all of which were printed in the Transactions of the Optical Society between 1922 and the date of publication. They are as follows:

The Optical Cosine Law; also a Note on the Cosine Law
The Addition of Aberrations
The Distribution of Corrective Duties in Optical Instruments
A General Solution of the First Order Aberrational Equations
A General Survey of the Thin Double Lens
A Reference System for Primary Aberrations
The Primary and Secondary Constant Magnification Surfaces of Thin Lenses

The Relation between Aperture, Axial Thickness, and Form for a Single Lens

A Large Aperture Aplanatic Lens not Corrected for Color

The Back Vertex Power of a Combination of Lenses

The Theory of Neutralization

Note on Chalmers' Applications of the Hartmann Test

The Treatment of Reflection as a Special Case of Refraction

On the Light Transmitted and Reflected by a Pile of Plates (Smith and D. S. Perfect)

The next group of papers by Mr. J. Guild includes the following titles:

An Equipment for Visual Spectrophotometry

The Transformation of Trichromatic Mixture Data: Algebraic Methods

The Geometrical Solution of Colour Mixture Problems

A Trichromatic Colorimeter Suitable for Standardization Work

A Criticism of the Monochromatic-Plus-White Method of Colorimetry

On a New Method of Colorimetry

A New Flicker Photometer for Heterochromatic Photometry

A Sensitive Optical Lever Method for Measuring the Thermal Expansion of Small Specimens

Mr. J. W. T. Walsh has contributed reprints of his papers entitled:

Radiation from a Perfectly Diffusing Circular Disc.

The Theory of Luminescence in Radioactive Luminous Compound

The Photometry of Projection Apparatus

The Effect of Slightly Selective Absorption in the Paint used for Photometric Integrators.

The Colour Temperature and Luminous Efficiency Relation for Tungsten, by H. Buckley, L. J. Collier and F. J. C. Brookes is next encountered; followed by Some Notes on Electric Incandescent Lamps for Use as Sub-Standards in Photometric Laboratories, and the Maintenance of the Unit of Candle-Power by means of Such Lamps, by W. Barnett; The Performance and Design of the Optical System of Ships' Navigation Lanterns, by E. H. Rayner; and Measurement by Optical Projection, by G. A. Tomlinson.

A. E. RUARK